Starshade Mechanical to TRL-5

Starshade Mechanical Architecture & Technology Update

SPIE 2019

Presented by David Webb

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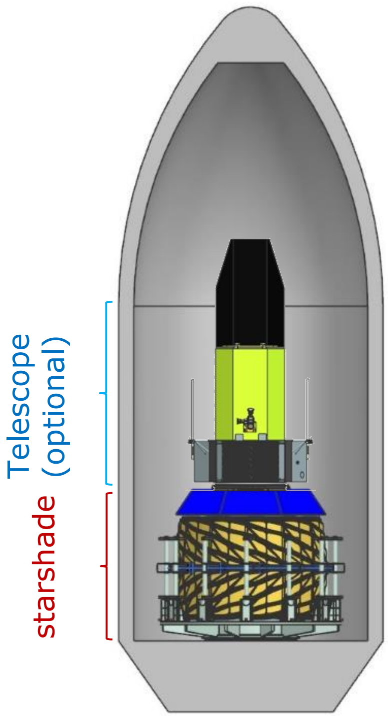
CL#19-5464

August 13, 2019

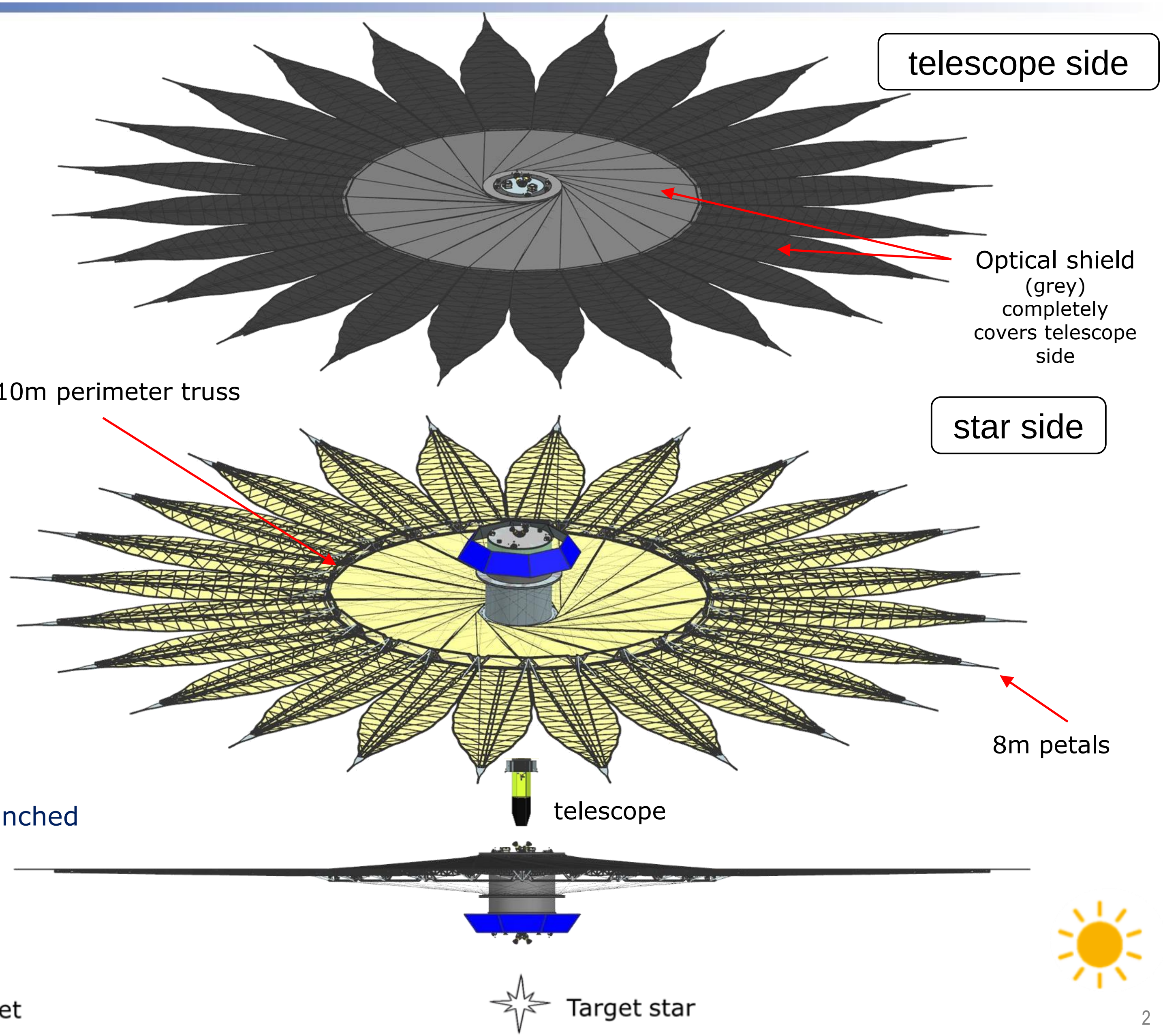
This research was partially carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics ands Space Administration.

Starshade S5 Baseline Design

26m NI2 design with 8m petals

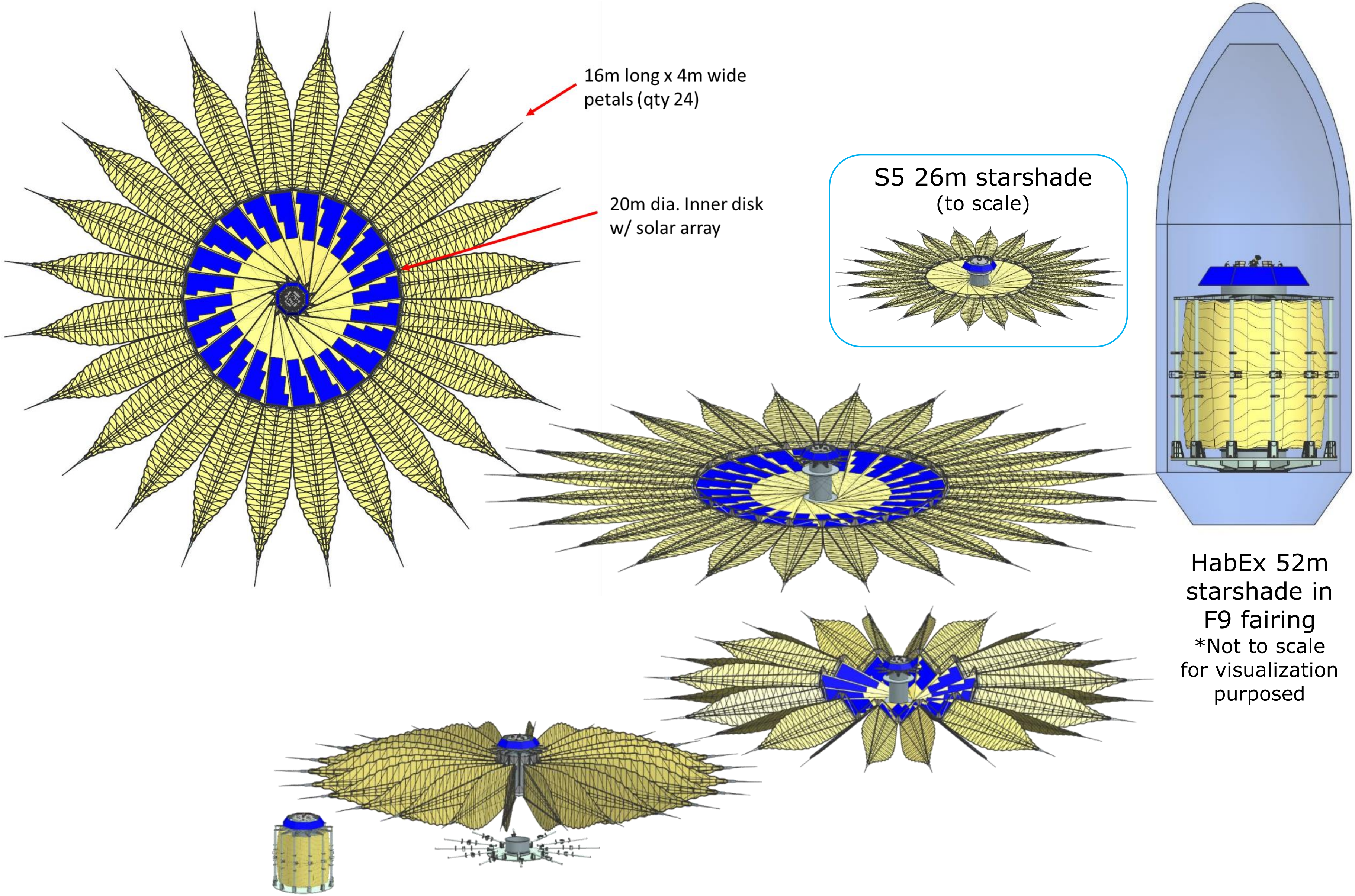


Stowed config shown co-launched
w/1.1m telescope
(5m fairing)



Exoplanet

HabEx 52m Starshade



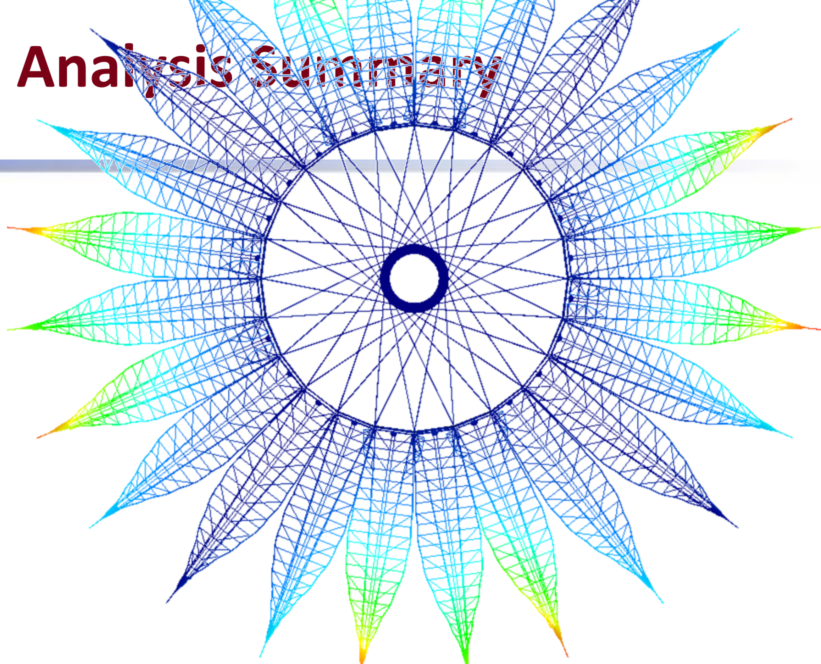
Mechanical System Structural Analysis Summary

26m Stowed Analysis Summary

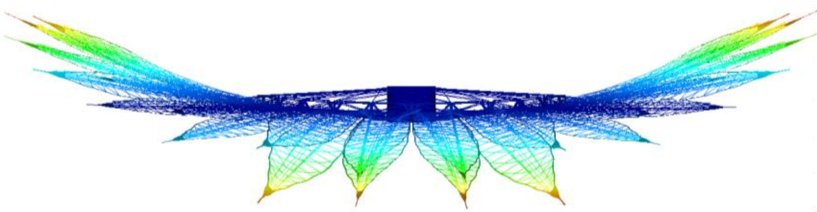
- Meets all stiffness and strength requirements including placement of telescope co-launched on top of starshade

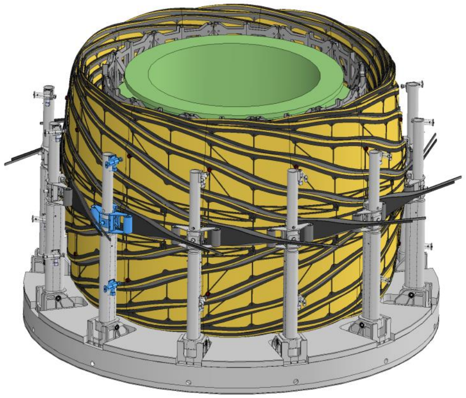
Deployed Analysis Summary

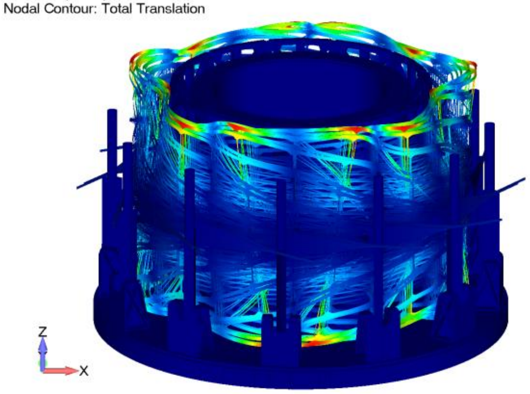
- S5: 1st mode > 1 Hz, 1st, in-plane = 17.3 Hz
- HabEx: 0.8Hz
- Structure stable (truss buckling or loss of tensions, accelerations/thermal)



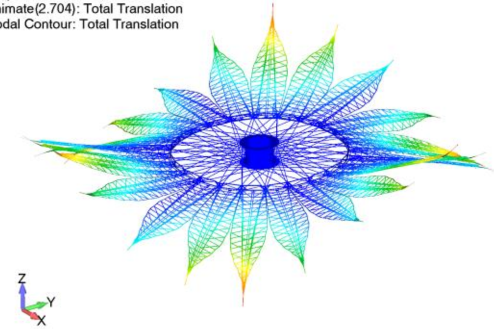
52m HabEx 1st Mode: 0.8 Hz



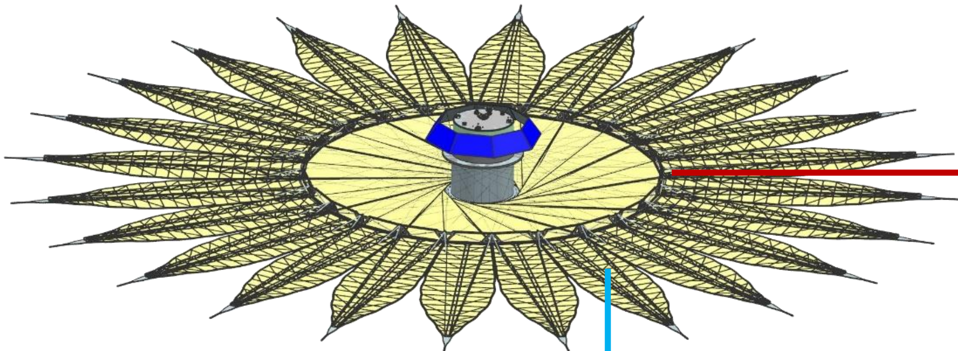


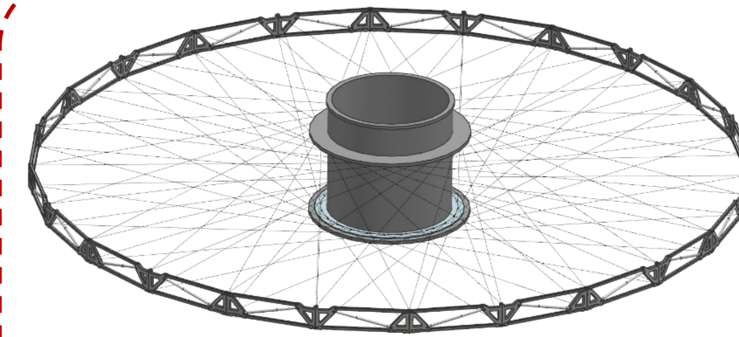


26m S5 1st Mode: ~1 Hz

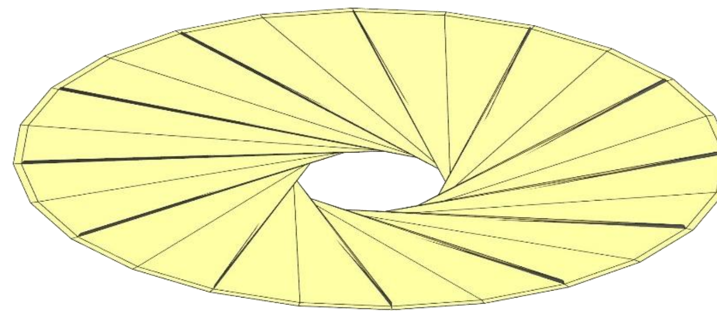


Subsystem Definitions



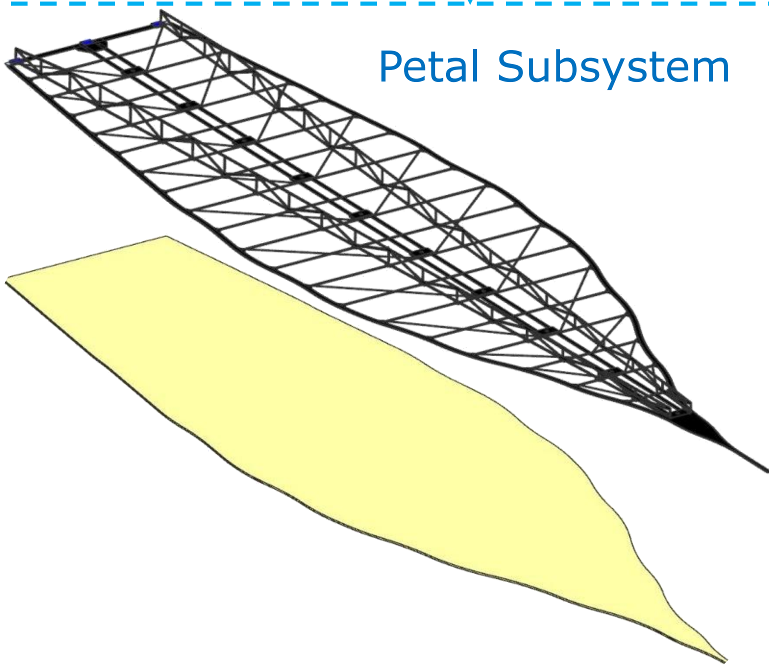


Truss + spokes + hub constitute separable structure w/defined interfaces to petal

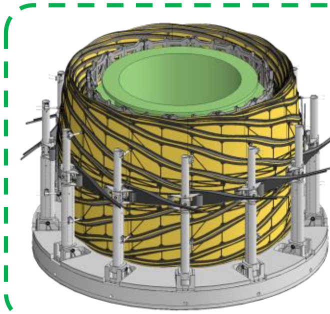


Inner Disk Subsystem

Petal Subsystem



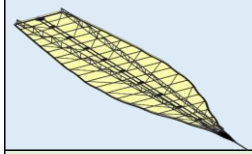
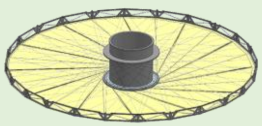
Petal developed, manufactured & assembled separate from inner disk, with defined interfaces at its base



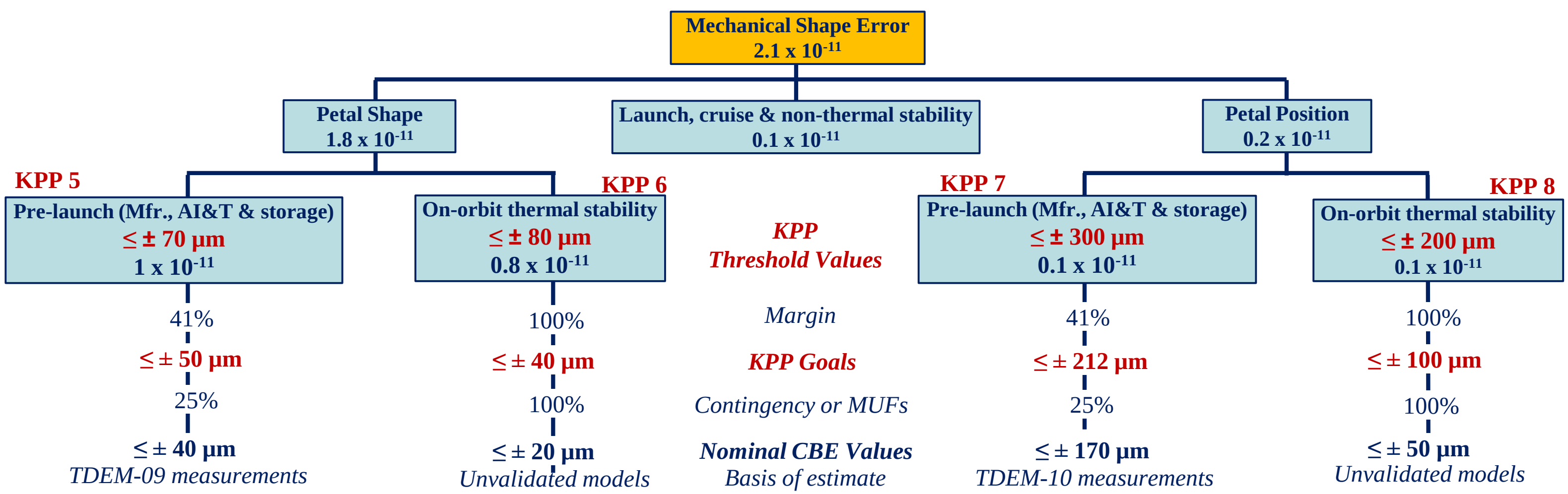
Petal Launch Restraint & Unfurl Subsystem (PLUS)

PLUS controls petal deployment & defines petal L/R interfaces (jettisoned after launch)

Mechanical Subset of KPP's & Error Budget

Technology Gaps	KPP #	KPP Specifications	KPP Threshold Values		KPP Goals
Petal Shape 	5	Verify **pre-launch accuracy** (manufacture, AI&T, storage)	$\leq \pm$ 70 μm	1 x 10^{-11}	$\leq \pm$ 50 μm
	6	Verify on-orbit **thermal stability**	$\leq \pm$ 80 μm	5 x 10^{-12} *	$\leq \pm$ 40 μm
Petal Position 	7	Verify **pre-launch accuracy** (manufacture, AI&T, storage)	$\leq \pm$ 300 μm	1 x 10^{-12}	$\leq \pm$ 212 μm
	8	Verify on-orbit **thermal stability**	$\leq \pm$ 200 μm	5 x 10^{-13}	$\leq \pm$ 100 μm

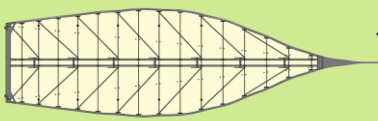
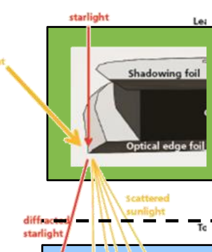
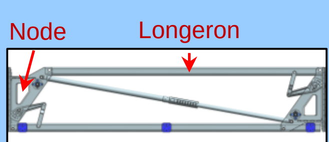
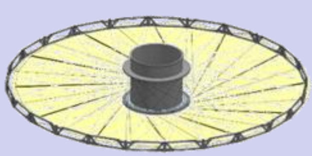
**KPP #6 & 8 represented the largest unverified mechanical shape error contributor to contrast in the error budget prior to S5 project*



KPP Verification Activities Flow Chart

Decadal Input

Reference Mission:
26m starshade, 10m disc, 8m long x 2m max width petals (qty 24)

	KPP Risk Reduction Activities (critical environments for KPP's)	Remaining TRL-5 Activities
Petal Subsystem  *2m wide x 8m long*	*Medium fidelity w/ KPP relevant features* *Article 1: 1.5m wide x 4m long*	*Medium fidelity w/ all features* *Article 2: 1.5m wide x 6m long*
 **Optical Edge (Segment, ~1m long)**	*Edge Scatter* *Medium fidelity edge assembly* *Half length (0.5m)*	
Inner Disk Truss Bay Assy  *~1.3m long*	*Medium fidelity w/ KPP relevant features* *Component level: longeron & node assemblies (full scale)*	*Medium fidelity w/ all features* *Assembly level: Truss Bay @ full scale (~1.3m long)*
Inner Disc Subsystem (IDS)  *10m diameter*	*Medium fidelity truss & spokes; optical shield w/ KPP relevant features* *Full Scale (10m dia)*	*Upgrade optical shield to medium fidelity also incl. petals* *Full Scale (10m dia)*

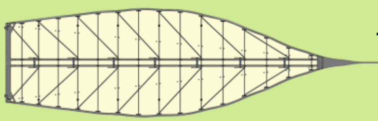
Petal Activities Flow Chart w/ Activity Status

Decadal Input

KPP Risk Reduction Activities
(critical environments for KPP's)

Remaining TRL-5 Activities

Petal Subsystem



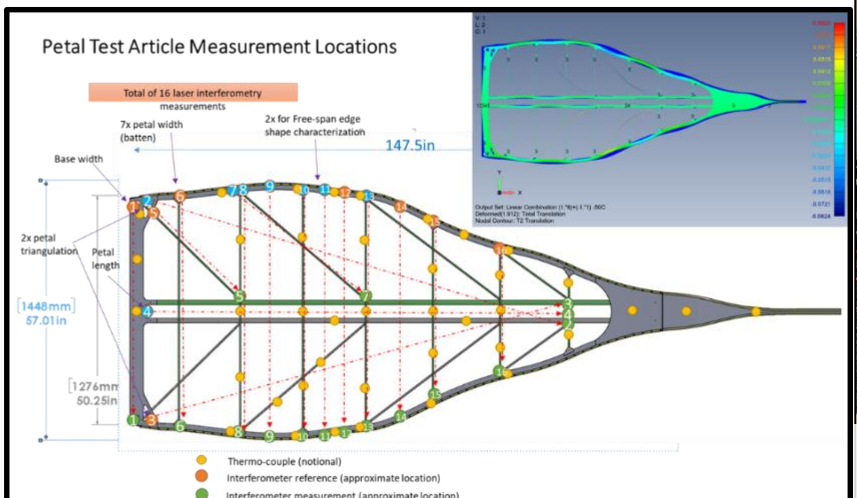
→ *Medium fidelity w/ KPP relevant features*

Article 1: 1.5m wide x 4m long

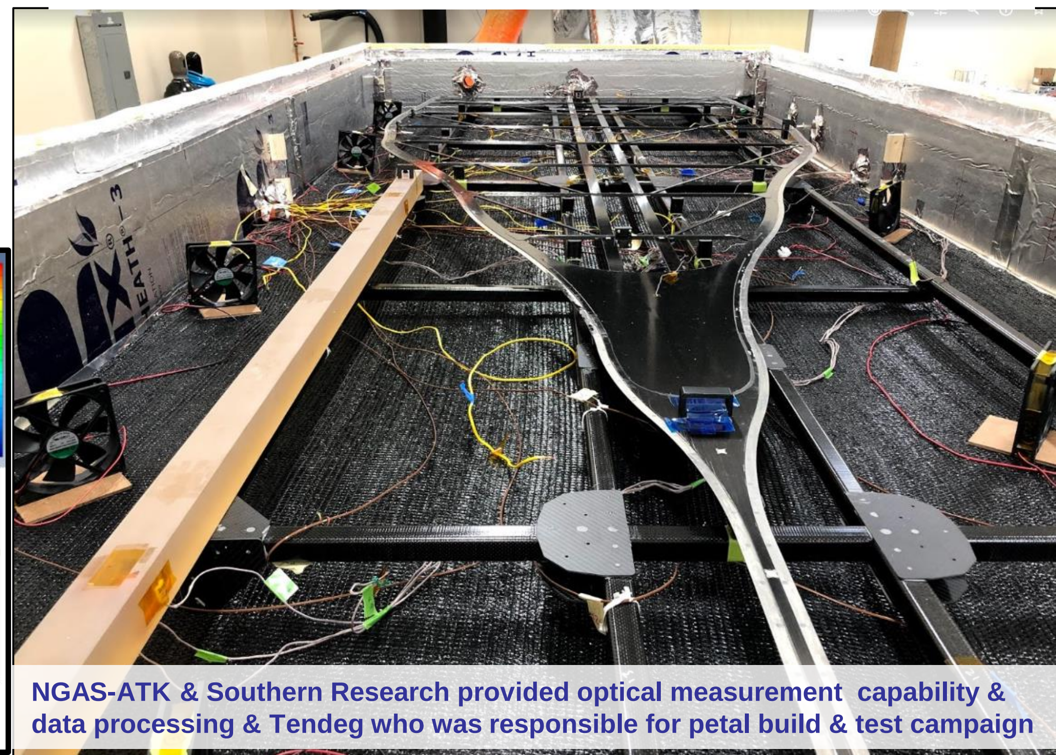
→ *Medium fidelity w/ all features*

Article 2: 1.5m wide x 6m long

- Shape vs temp. test complete @ 5 micron accuracy, model validation on-going, preliminary results show large margin on requirement
- Shape post thermal cycle extremely stable (repeatable to a few microns)
- Deploy cycle (unfurl) & shape meas. upcoming



Petal in thermal chamber at Tendeg Facility in Louisville, Co.



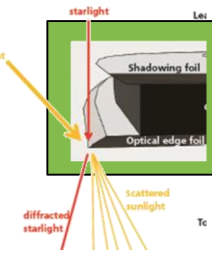
NGAS-ATK & Southern Research provided optical measurement capability & data processing & Tendeg who was responsible for petal build & test campaign

Optical Edge Activities Flow Chart w/ Activity Status

Decadal Input

KPP Risk Reduction Activities
(critical environments for KPP's)

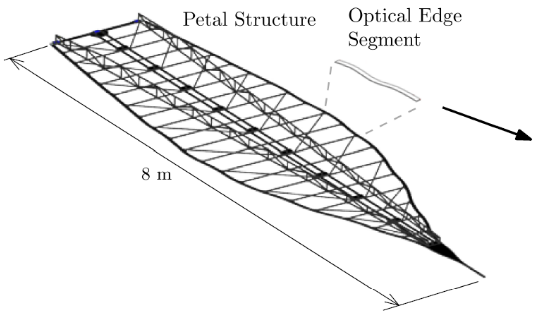
Remaining TRL-5 Activities

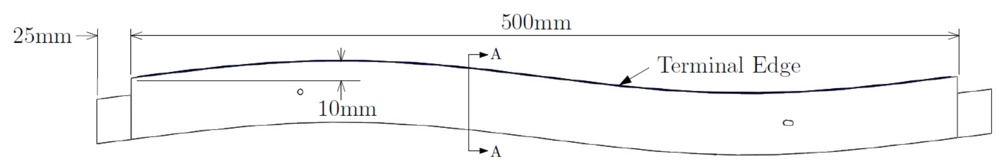


Optical Edge (Segment, ~1m long)

Edge Scatter
Medium fidelity edge assembly
Half length (0.5m)

- **Pathfinder edges thru environments**
- **In-plane shape and scatter performance preserved & meet reqts**
- **Evan Hilgemann (edge lead engineer) has talk on this next**





Half length (0.5m) edge prototype
(top – telescope side, bottom – Star side)

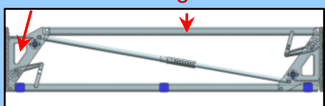
Truss Bay Activities Flow Chart w/ Activity Status

Decadal Input

KPP Risk Reduction Activities
(critical environments for KPP's)

Remaining TRL-5 Activities

Inner Disk Truss Bay Assy



~1.3m long

→ *Medium fidelity w/ KPP relevant features*

Component level: longeron & node assemblies (full scale)

→ *Medium fidelity w/ all features*

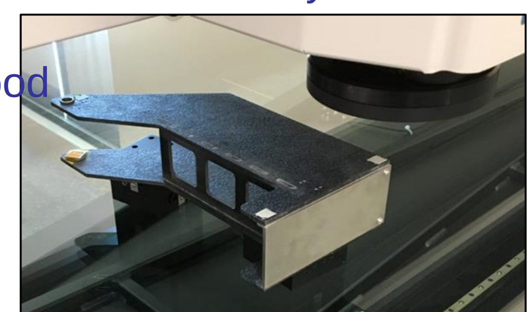
Assembly level: Truss Bay @ full scale (~1.3m long)

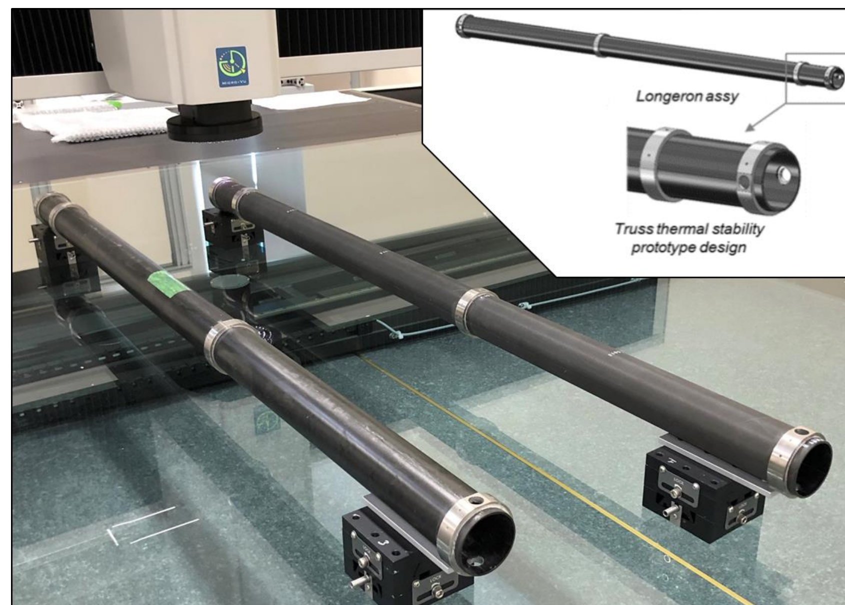
Longeron assemblies:

- Length vs temp. meets reqs (1 of 3 meas.)
- Post thermal cycle dimensional stability meets reqs (2 of 3 meas.)

Node Assembly:

- Testing and model validation in process
- Post thermal cycle dimensional stability meets reqs (2 of 3 meas.)
- Material data looks good





Node assy (left) & longeron assys (right) on Micro-Vu Measurement Maching at Tendeg Facility in Louisville, Co.
Length vs. temp measurement at NGAS-ATK in San Diego in IMF (interferometric measurement facility)

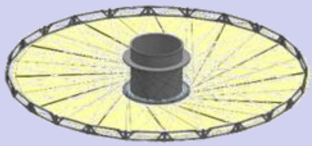
Inner Disk Activities Flow Chart w/ Activity Status

Decadal Input

KPP Risk Reduction Activities
(critical environments for KPP's)

Remaining TRL-5 Activities

Inner Disc Subsystem (IDS)



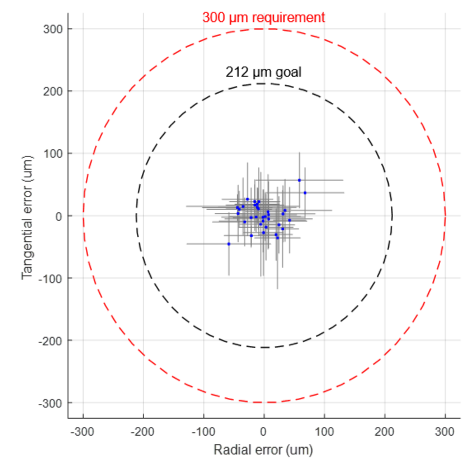
10m diameter

→ ***Medium fidelity truss & spokes; optical shield w/ KPP relevant features***

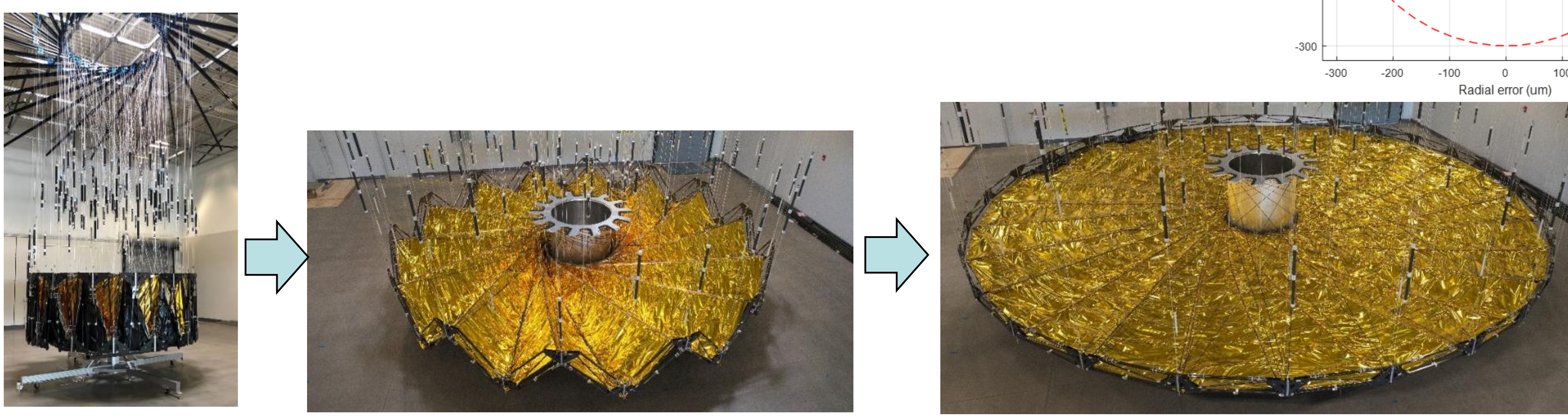
Full Scale (10m dia)

→ ***Upgrade optical shield to medium fidelity also incl. petals***

Full Scale (10m dia)

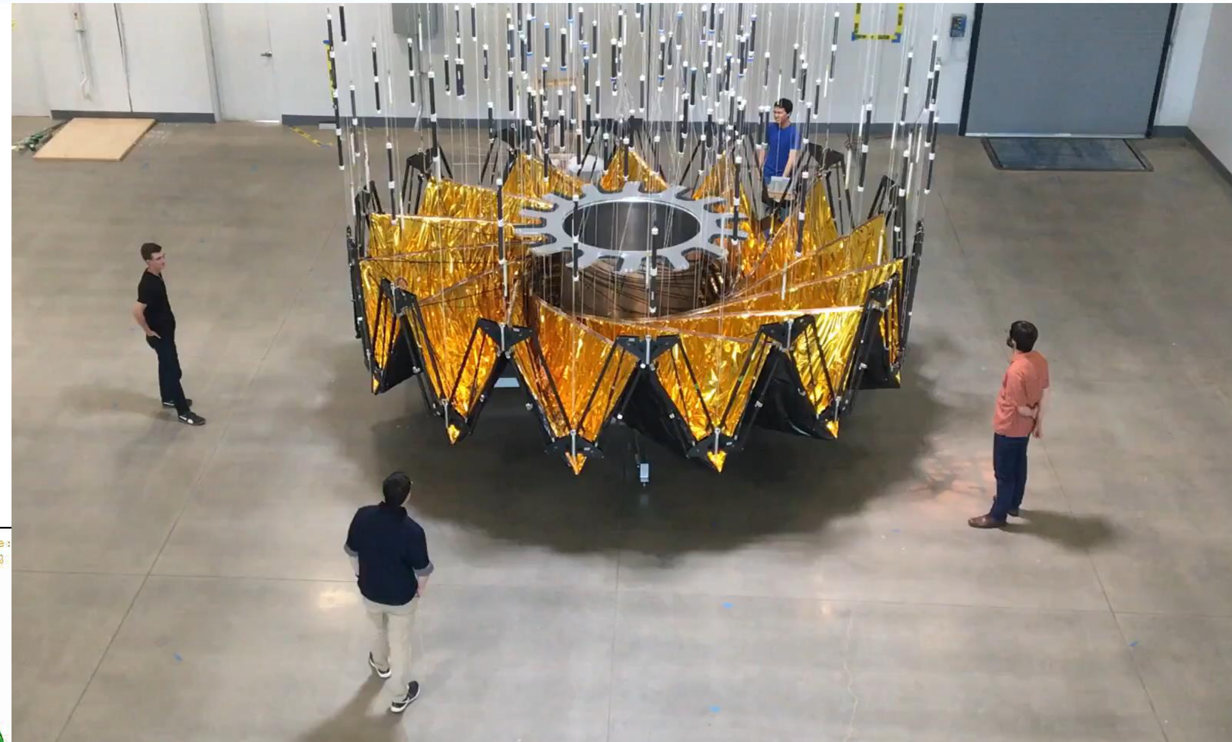


- Multiple successful deployments of 10m (full scale) Inner Disk Subsystem w/ truss, spokes and optical shield
- Deployment accuracy to date well within requirements (10x 10%, 3x 50%, 3x 80% and 1x full stow, more coming)
- Deployment FEA modeling efforts ongoing

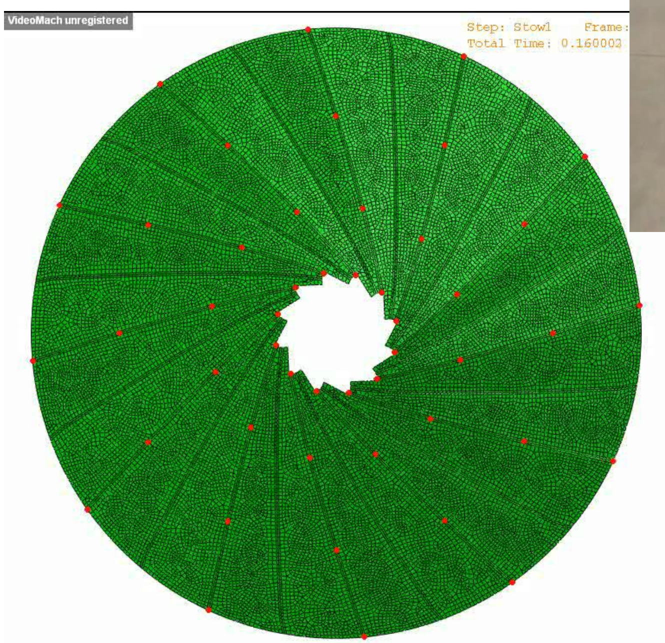


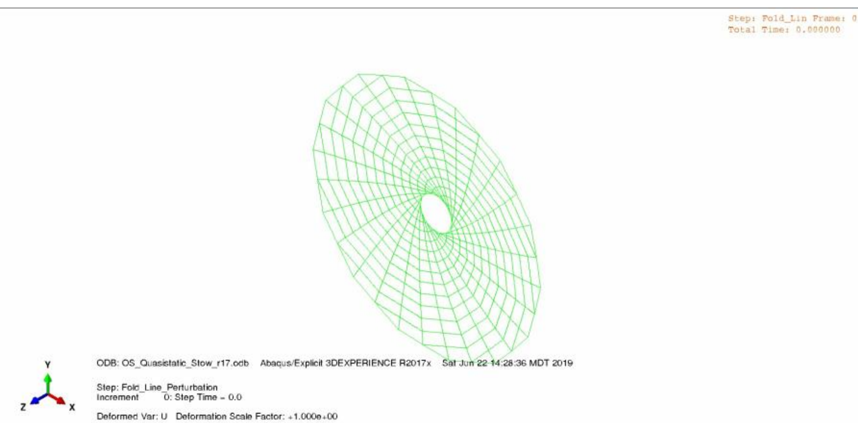
Truss & shield at Tendeg Facility in Louisville, Co., measurements made with JPL Leica laser tracker

Inner Disk Deployment



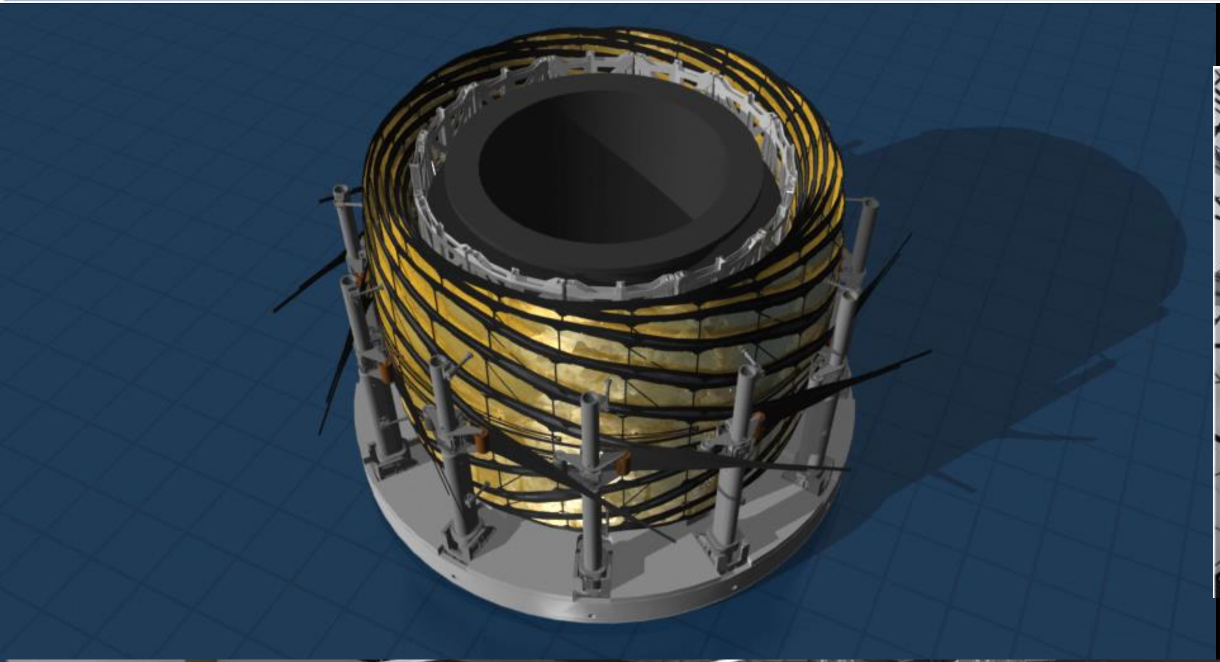
Truss & shield deployment at Tendeg Facility in Louisville, Co.





Shield furling FEA developed by Roccor (Longmont, Co)

Petal Unfurl Subsystem Engineering Work



- PLUS testbed w/full set of petal has been deployed and characterized
- Future work to include test of 4x medium fidelity petals (CFRP) with upgraded interfaces and offloading to validate against deployment model

Backup Charts

TRL-5 Test Activities Flow Chart

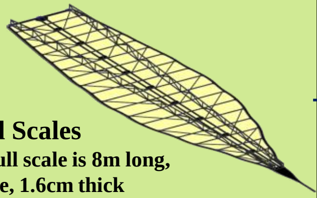
Reference Mission:
26m starshade, 10m disc, 8m long x 2m max width petals (qty 24)

Risk Reduction Activities
(TRL-4 + critical environments for KPP's)

Decadal Input (Mar '20)

Remaining TRL-5 Activities

Petal Subsystem



Mixed Scales
Note: full scale is 8m long, 2m wide, 1.6cm thick

Article 1: 1.5m wide x 4m long x 1.6cm thick

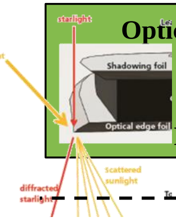
*B.1 Measure, as reference, **as-manufactured** petal 2d edge profile, then verify petal shape after:*
B.2 – deploy cycles,
***B.3 - thermal cycles** (deployed)*

→ *Validate analytical model of*
B.4 – critical dimension vs. temperature
B.5 Petal shape response vs. I/F load

Article 2: 1.5m wide x 6m long x 1.6cm thick

→ ***B.1 Verify** petal 2d edge profile of Article 2 as-manufactured*
*Repeat tests **B.2, B.3, B.4, B.5***
***B.7 Verify** petal shape **after** storage (creep)*

Optical Edge (Segment)



Half Scale (0.5m long)

***B.1 Verify** petal 2d edge profile, then edge scatter:*
***B.2** –across all angles at discrete locations*
***B.3** – across entire edge at broad angle*

→ *Verify B.1, B.2, B.3 after:*
B.4 – deploy cycles,
thermal cycles: B.5 deployed & B.6 stowed
B.7 critical dim. vs temp
B.8 long term stow (creep)

Inner disc Truss Bay Assy

Full-Scale: (1.3-m long)

Sub-assembly level: longeron & node assemblies

Verify critical dimensions of Truss Longeron & Node assemblies:
A.1 - as-manufactured
A.2 - after thermal cycles

→ *Validate analytical model of Truss Longeron & Node assembly via measurement of critical dimension vs.:*
A.4 – I/F Load
A.5 – temperature

** At relevant scale*

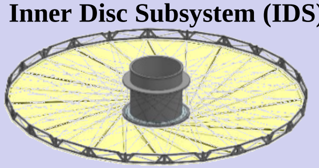
Assembly level: Truss Bay

→ *Verify Truss Bay critical dim.*
A.6 – as-manufactured
A.7 - after thermal cycles (deployed)

→ *Validate Truss Bay model of critical dimension vs.:*
A.8 – I/F Load
A.9 – temperature

A.3 – verify dim. @ sub-asssy level after storage (creep)

Inner Disc Subsystem (IDS)



Full-Scale (10-m dia.)

IDS structure @ med-fid, shield @ low-fid

***C.2 Validate** Disc analytical model via I/F load / petal position*

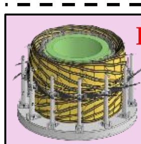
→ ***C.1 - Verify** repeatable Disc **deploy tolerances w/ TRL-4 Optical Shield** installed*

IDS incl. shield @ med-fid

→ ***C.3** - Verify repeatable disc **deploy tolerances w/ TRL-5 Optical Shield** installed (after verifying shield opacity)*

→ ***C.4** - Verify OS opacity at truss-bay & petal I/F's*

→ ***C.5 Validate** disc model of **deployment kinematics***



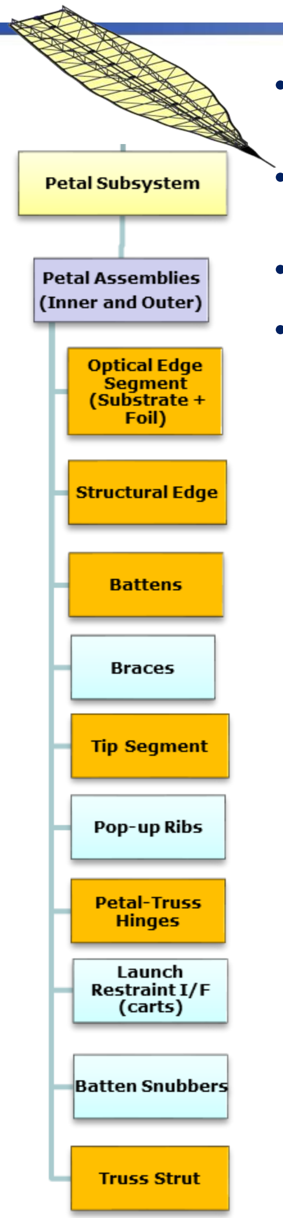
Deployment Control Subsystem (DCS)
Full-Scale (2.25-m stow dia.)

→ ***D.1 Verify** DCS unfurls with no edge contact*

→ ***D.2 Validate** DCS model of **deployment kinematics***

→ *Additional PLUS sub-assy test verification work if necessary (e.g. vibe, cold test)*

Test Article 2 Description
Milestone 5B & 6B



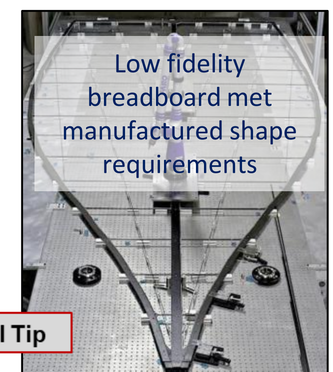
- **Tests**: Verify petal shape as manufactured, shape stability after deploy & thermal cycles & storage (creep), Validate petal model of shape vs. temperature
- **Critical components for tests**: battens*, optical edge, tip, interfaces to truss, & secondarily: braces, spines, interfaces to PLUS (batten length defines petal width*)
- **Scale**: Half (0.65m wide at base, 4m long), medium fidelity (or better)
- **Components**:
  - Materials are medium fidelity (space-flight compatible)
  - Battens are uniaxial pultruded CFRP** COTS material, incl. batten snubbers
  - Optical Edge & Tip Assy's are COTS MBF23 Ni/Fe alloy amorphous metal (MBF23) sandwiched with quasi-iso CFRP* plate, room temp epoxy (reviewed TRL-5 activity developing that product, not discussed in detail here)
  - Interfaces to truss: petal strut assy & petal to truss hinge assemblies (invar hinges)
  - Optical shield including close-outs
  - Spines including carts launch restraints, braces, rib assy

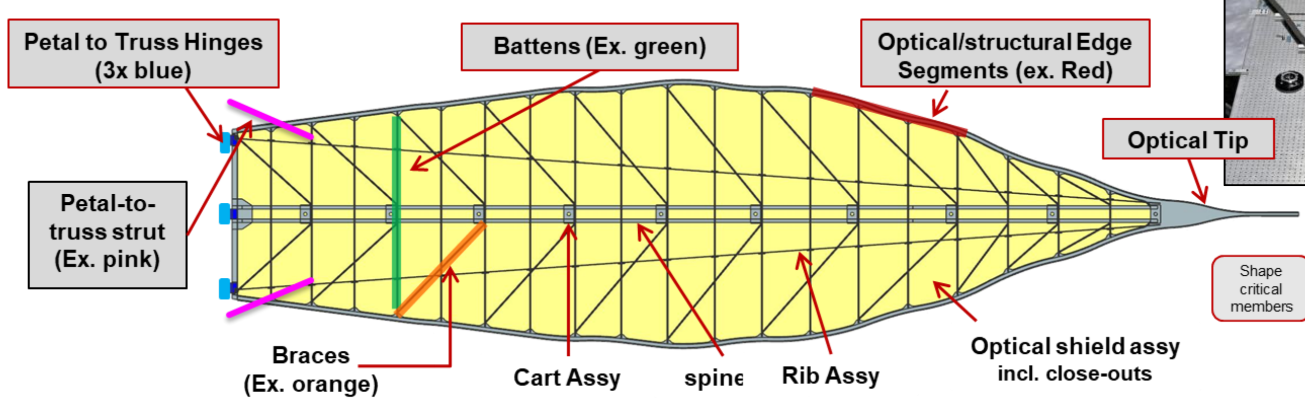
* M55J with cyanate ester resin, per shared NG materials assumption

** T700S data is measured data from JPL SWOT flight program

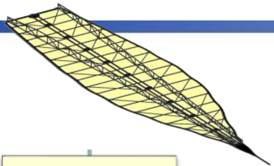
*** Critical components boxed in red below, orange on left

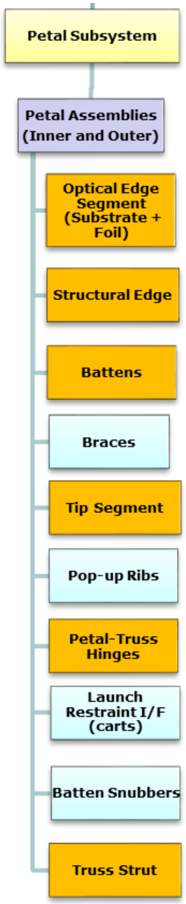
**** Materials are medium fidelity (space-flight compatible)





Petal Test Articles 1 & 2 Description

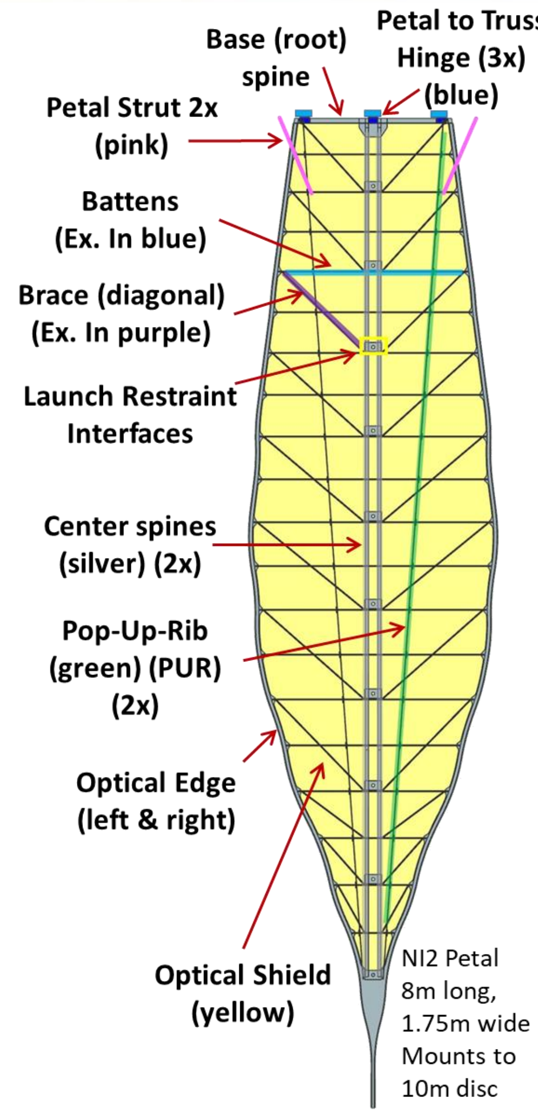




Article 1 key purpose: validate petal model and performance for structure response to temperature (key & driving petal components present)

Article 2 key purpose: demonstrate remaining environments with all components present

		Article 1 Milestones 5A & 6A		Article 2 Milestones 5B & 6B	
Scale:	Full: 2m wide 8m long 1.6cm thick	1.5m wide **4m** long 1.6cm thick	Relevant Components Present for Test	1.5m wide **6m** long 1.6cm thick	Relevant Components Present for Test
Components	Optical Edge	correct materials & construction, not sharp or shape accurate		Medium Fidelity	
	Tip Segment				
	Structural Edge	medium fidelity			
	Battens				
	Braces				
	Pop-up Ribs	not present			
	Petal-truss hinges	I/F only			
	Launch Restraint I/F (carts)	not present			
	Batten snubbers				
	truss strut				
	Petal Shield	form/fit only (for deployment demo funcition only)			
Tests	Verify shape Accuracy	NO (shape measured as reference only)	Structure + Edge	YES	Structure + Edge
	deploy cycles	YES	Structure + Edge		Structure + Edge + Shield
	thermal cycles (deployed)	YES	Structure + Edge		Structure + Edge
	critical dimension vs temperature (Validate Thermal Deformation Model)	YES	Structure + Edge		Structure + Edge + Shield
	petal shape response vs I/F load (Validate Structural Model)	YES	Structure + Edge		Structure + Edge + base hinges + Truss Strut
	long term storage (creep)	NO	N/A		Structure + Edge + base hinges



Inner Disk Test Articles for Milestones 7B Description

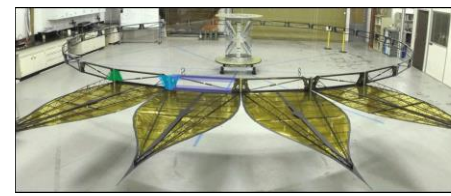
- Truss Assembly
  - Node Assy
  - Cable spooler/motor Assy
  - Truss-Hub Restraint I/F
  - Longeron incl. Petal Hinge I/F
  - Shorteron
  - Diagonal Assy
  - Spokes Assy

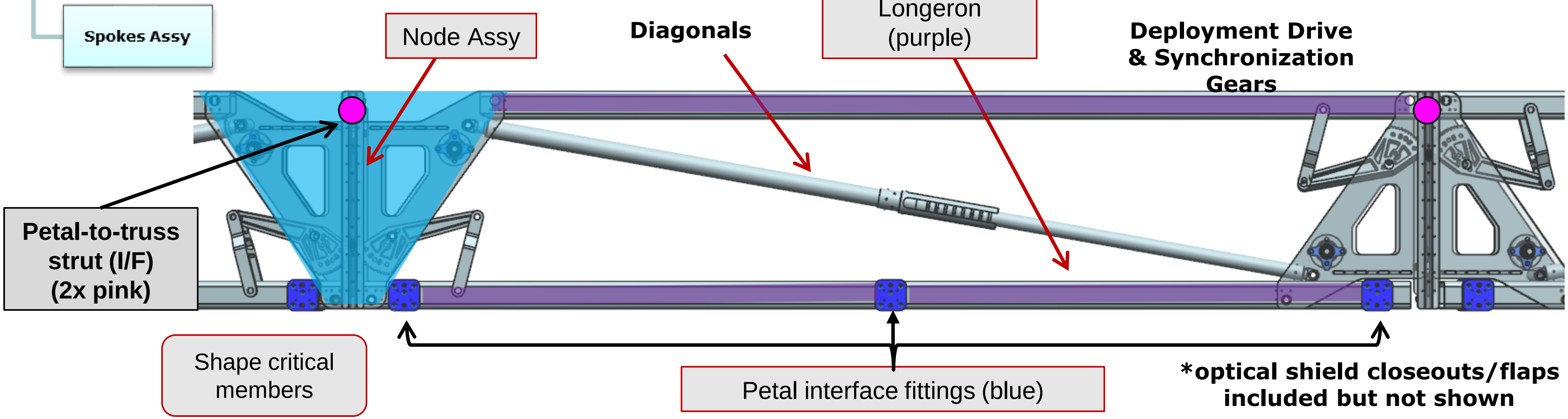
- **Tests**: Verify truss bay dimensions (manufacture), Validate Truss Bay model of length vs. temperature
- **Critical components for tests**: longeron & node
  – average longeron length + node width defines the disc radius (petal position)
- **Scale**: Full (1.3-m long) Truss Bay assembly of medium fidelity (or better)
- **Components:**
  – Longerons are quasi-iso CFRP* tubes with invar petal I/F fittings & I/F to gear assy's
  – Nodes are quasi-iso CFRP* plates with CFRP 'clips' (jointery) & I/F to gear assy's
  – Diagonals are quasi-iso CFRP* tubes with invar end fittings
  – Optical shield close-outs/flaps included (black kapton XC), (not shown in image)
  – Interfaces to Petal: Petal Strut & Petal interface fittings (invar)

  *(M55J with cyanate ester resin, per shared NG materials assumption)

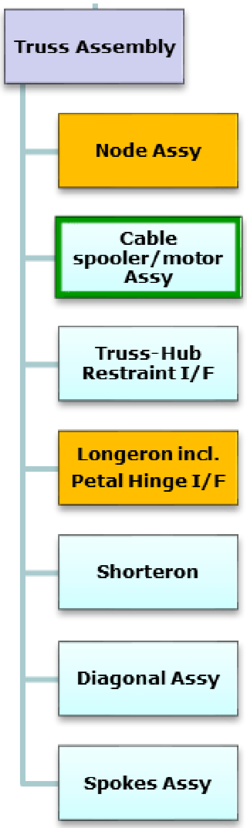
  ** Critical components boxed in red below, orange on left

  *** Materials are medium fidelity (space-flight compatible)





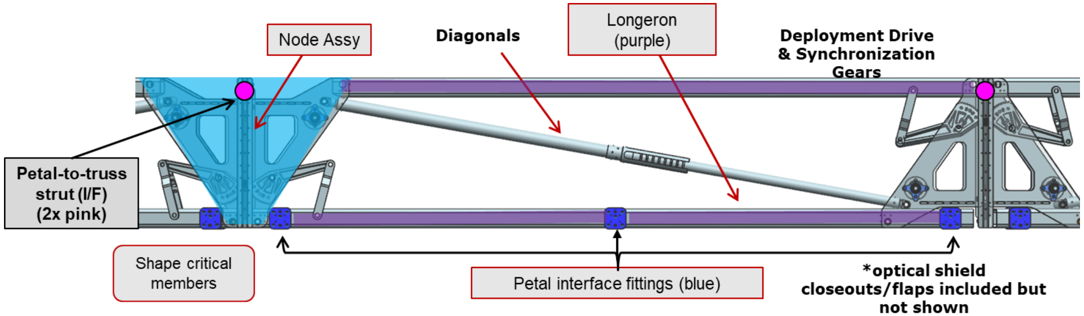
Inner Disk Test Articles for Milestones 7A & 7B Description



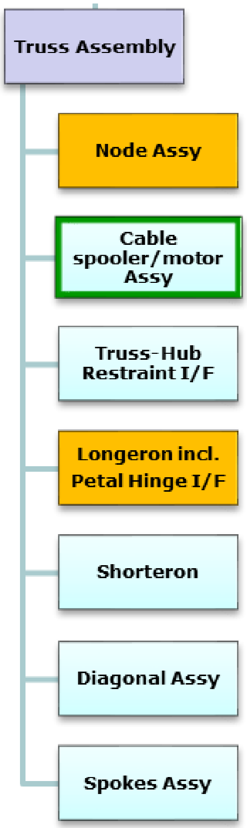
Milestone 7A hardware key purpose: Validate performance for critical dimension vs temperature at the *sub-assembly* level, longeron & node assemblies (key & driving components present)

Milestone 7B hardware key purpose: Validate performance for critical dimension vs temperature at the *assembly* level, longeron & node assemblies (key & driving components present)

		IDS for Milestone 7A		IDS Milestone 7B	
Scale:	**Full: ~1.3m long**	1/2 length or greater	Relevant Components Present for Test	Full	Relevant Components Present for Test
Components	**Level of Assembly**	Sub-assembly Level	↓	Assembly Level	↓
	Longeorn Assembly	medium fidelity		Medium Fidelity	
	Node Assembly	medium fidelity			
	Diagona Assembly	not present			
	thermal cycles (deployed)	YES	longeron & node assemblies		Truss Bay Assy (longeron, node, diagonal)
	critical dimension vs temperature (Validate Thermal Deformation Model)				
	long term storage (creep)	NO	N/A		longeron assy



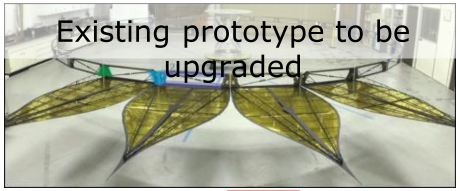
Inner Disk Test Articles for Milestone 7D Description

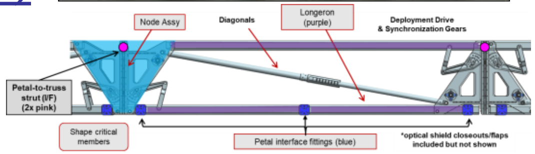


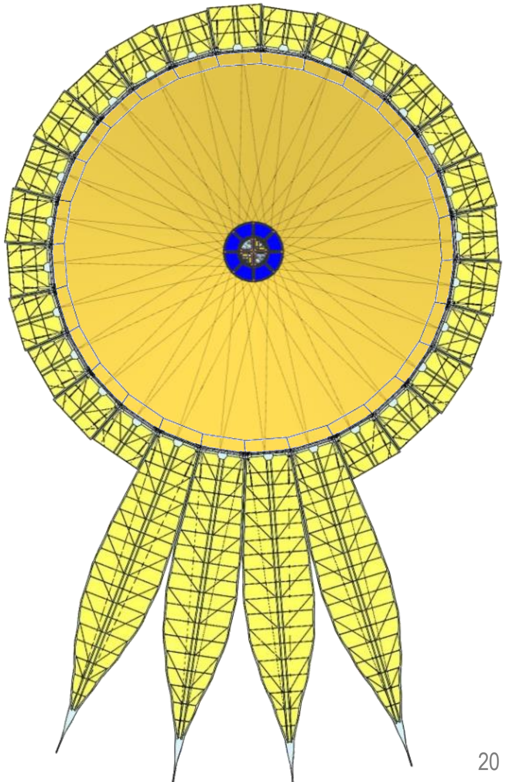
- **Tests**: Verify repeatable truss deployment tolerances with OS installed, Validate disc model of deployment kinematics, Validate disc model of shape vs. spoke load, Verify OS opacity at truss-bay & petal I/F's
- **Critical components for tests**: All truss components, spokes, optical shield, petals (bases + full simulators)
- **Scale**: Full (10m diameter) @ medium fidelity ***(upgrade of existing prototype)***
- **Components**:
  - Longerons/shorterons are quasi-iso CFRP* tubes with petal I/F fittings
  - Nodes are quasi-iso CFRP* plates w/ Al center beam
  - Diagonals are quasi-iso CFRP* tubes (Al end fittings)
  - CFRP spoke assemblies (metal fittings)
  - Central hub assy (Al)
  - Synchronization gear assemblies (Ultem)
  - Optical shield close-outs/flaps to petal simulators (black kapton XC)
  - Redundant drive spool/motor assemblies (Al/Steel)
  - Interfaces to Petal: Petal Strut & Petal interface fittings (Al)
    - Full petal simulations on 4 locations (all features, TBD matl.)
    - Petal bases suff. for petal-truss I/F on all bays (all features, TBD matl.)

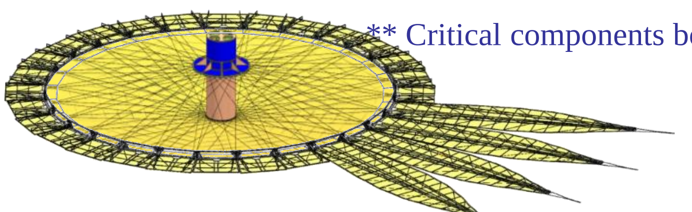
*(M55J with cyanate ester resin, per shared NG materials assumption)

** Critical components boxed orange on left tree









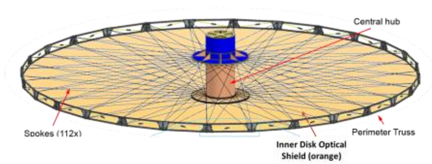
Inner Disk Test Articles for Milestones 7C & 7D Description

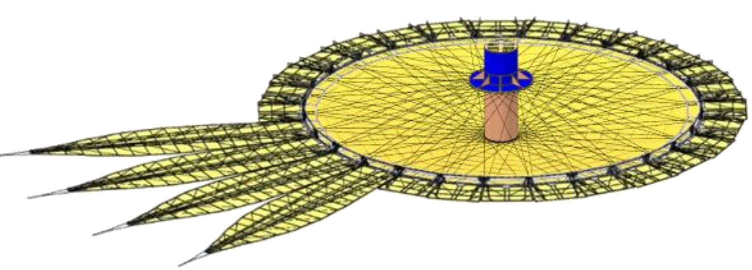
- Truss Assembly
  - Node Assy
  - Cable spooler/motor Assy
  - Truss-Hub Restraint I/F
  - Longeron incl. Petal Hinge I/F
  - Shorteron
  - Diagonal Assy
  - Spokes Assy

Milestone 7C hardware key purpose: Verify deployment performance of inner disk (perimeter truss) in the presence of an optical shield with deployment relevant features (key & driving petal components present)

Milestone 7D hardware key purpose: Verify deployment performance of inner disk (perimeter truss) with optical shield and petals with all relevant features

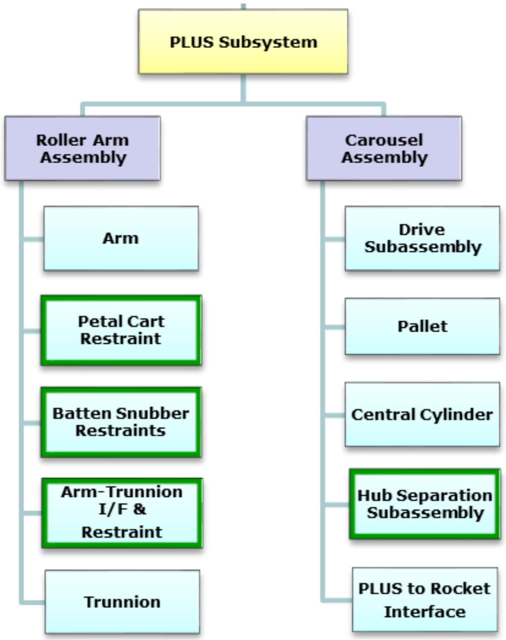
Existing prototype to be upgraded



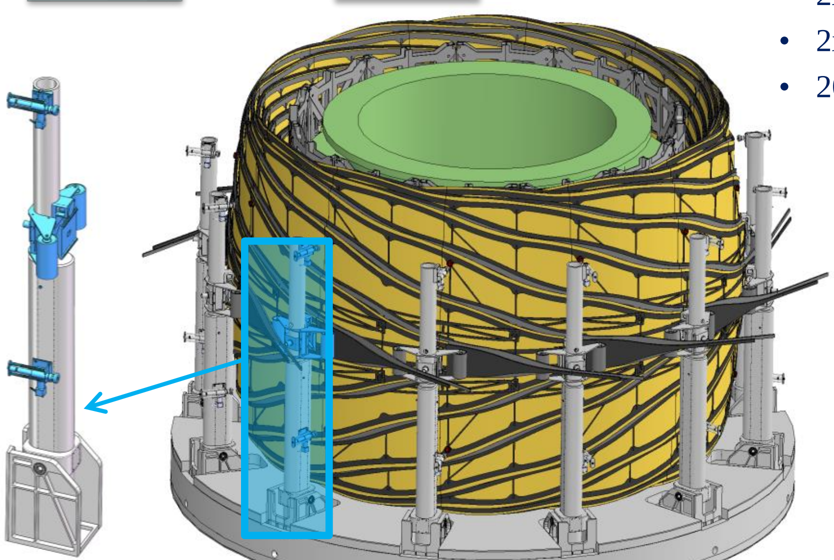


		IDS for Milestone 7C		IDS Milestone 7D	
Scale:	**10m diameter**	10m dia	Relevant Components Present for Test	10m dia	Relevant Components Present for Test
Components	**Perimeter Truss**	Medium Fidelity		Medium Fidelity (hub = form/fit/ function)	
	Spokes				
	Hub	form, fit & funciton sufficient			
	Optical Shield	Low Fidelity, deployment critical features present			
	4x full petal + petal stubs	not present			
	Inner disk shield to petal shield interface	not present			
	Inner disk shield to hub interface	not present			
Tests	**Verify shape Accuracy (deploy cycles)**	YES	Perimeter truss, spokes, hub	YES	Perimeter truss, spokes, hub
	disk shape response vs I/F load (Validate Structural				

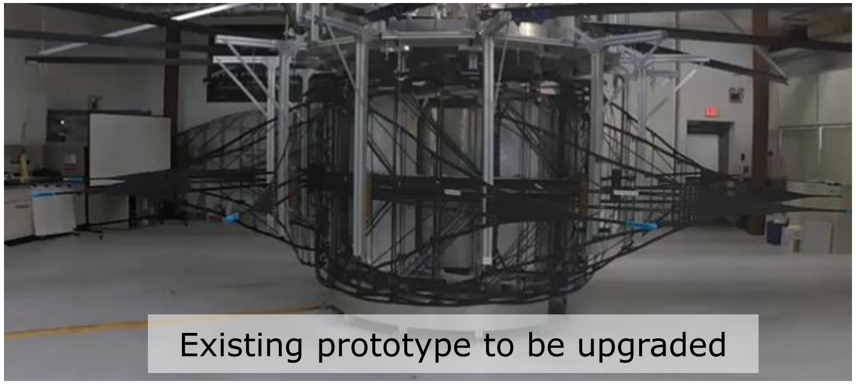
Test Article Description
Deployment Control System (PLUS)



- **Tests**: verifying no edge contact during unfurl and validate the analytical model of deployment kinematics
- **Critical components for tests**: Rollers incl. tip management, 2x 6m composite petals, 2x I/F petals and remaining simulators
  - Key components to enable medium fidelity petal unfurling
- **Scale**: Full 2.25m core + 6m petals (shortened length, full width/thickness ***(significant upgrade/overhaul of existing prototype)***
- **Components**:
  - Roller arm assemblies (all new, medium fidelity): rollers and tip management, batten snubber and cart restraints
  - Carousel motorized drive system (existing)
  - Petals: all petals incl. all features, e.g. rib assy's & optical shields, snubbers, carts
    - 2x 6m composite petals (new)
    - 2x interface petals (boundary condition for CFRP petals) (new)
    - 20 simulator petals (flexural stiffness of petal, existing in starshade lab)

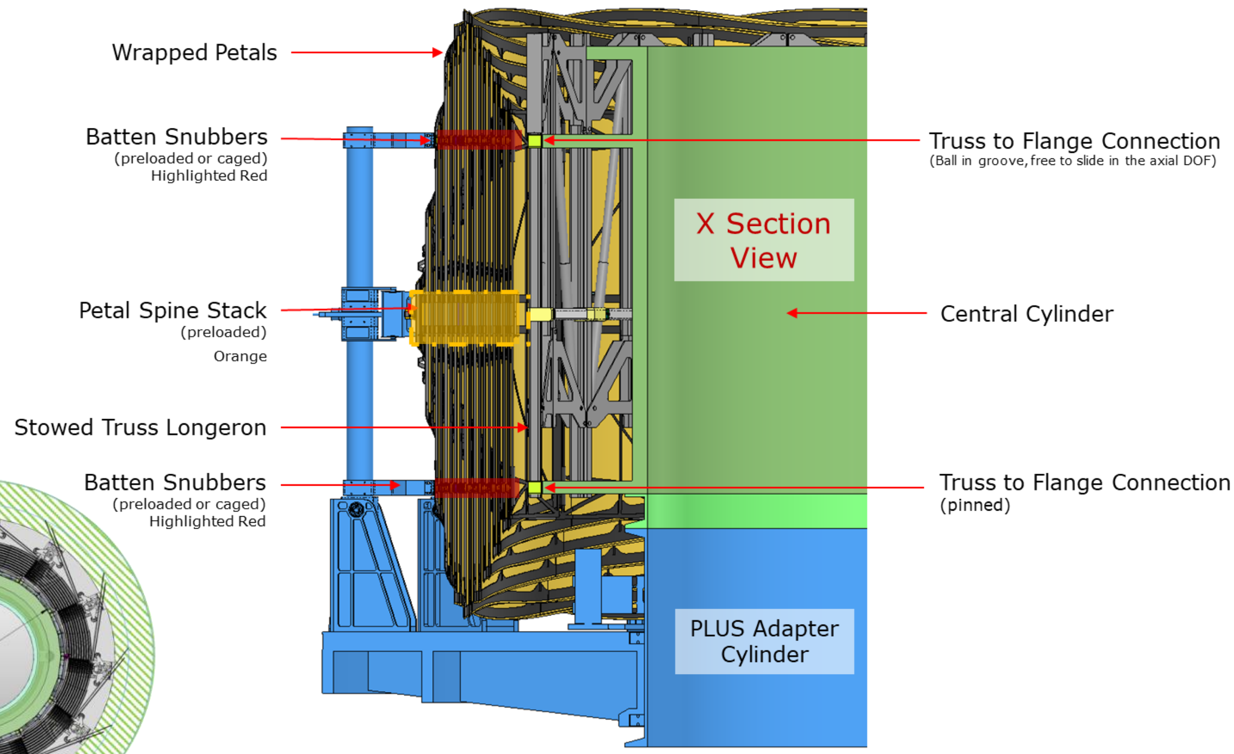


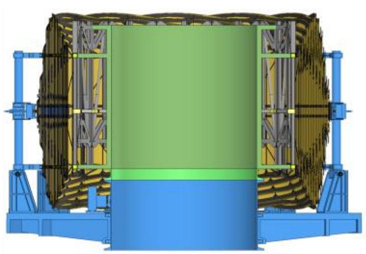
Roller Arm



Existing prototype to be upgraded

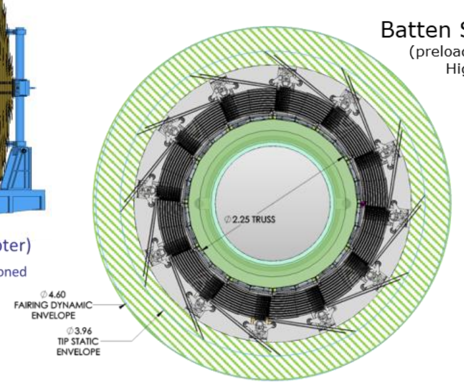
Cross Section View

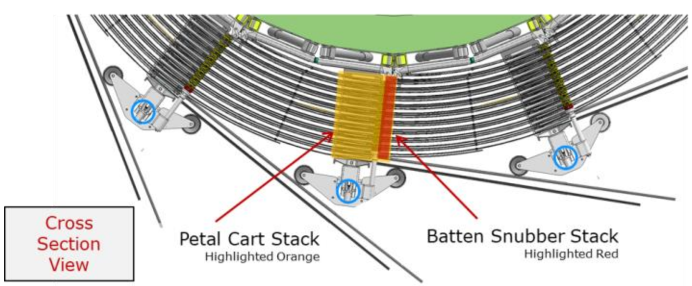




PLUS (Roller Arms, Carousel, PLUS Adapter)

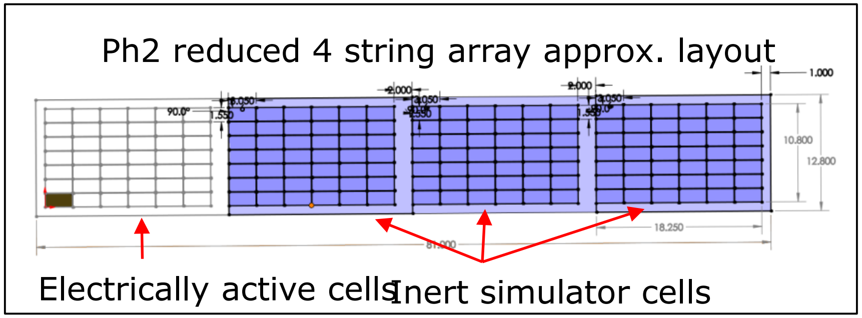
*** Roller-arm/carousel/plus adaptor assy jettisoned after launch (total mass = 608 kg)





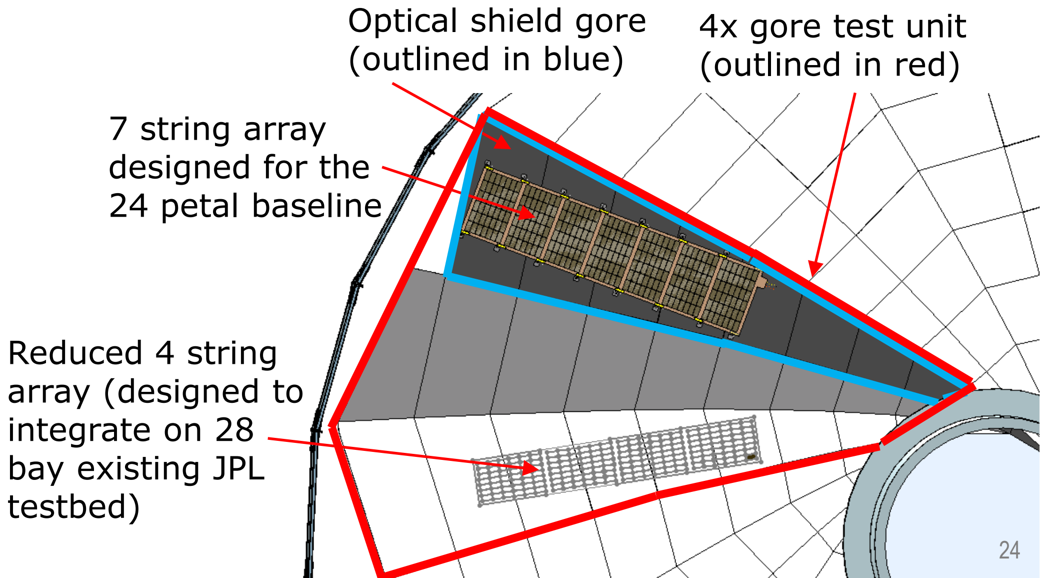
Optical Shield Solar Array SBIR
(Tendeg SBIR)

- Product Description:
  - SolAero is constructing a solar cell string of IMM cells to be assembled to the Tendeg starshade optical shield solar array for testing (an array is 4 strings combined in a frame structure that gets attached to an optical shield gore)
  - In one array, a single string will be electrically active for test verification. These cells will be IMM cells that are leftover and/or lower efficiency
- Risks
  - Matching the interaction of array and OS to create a simple, low risk stow and deploy
  - Individual cell breakage due some localized interference of adjacent OS, spoke, frame, cabling etc
- Testing:
  - Electrical continuity of IMM cell in stow/deploy from array to hub connector, frame to OS interface, cell mechanical survivability, CTE mismatch design, temperature limits
  - Testing to be performed on a standalone "quad-gore" (4x gores only), not in presence of the rest of the shield
  - Not tested – More than 4x string config in a frame, multiple string electrical routing, vibe

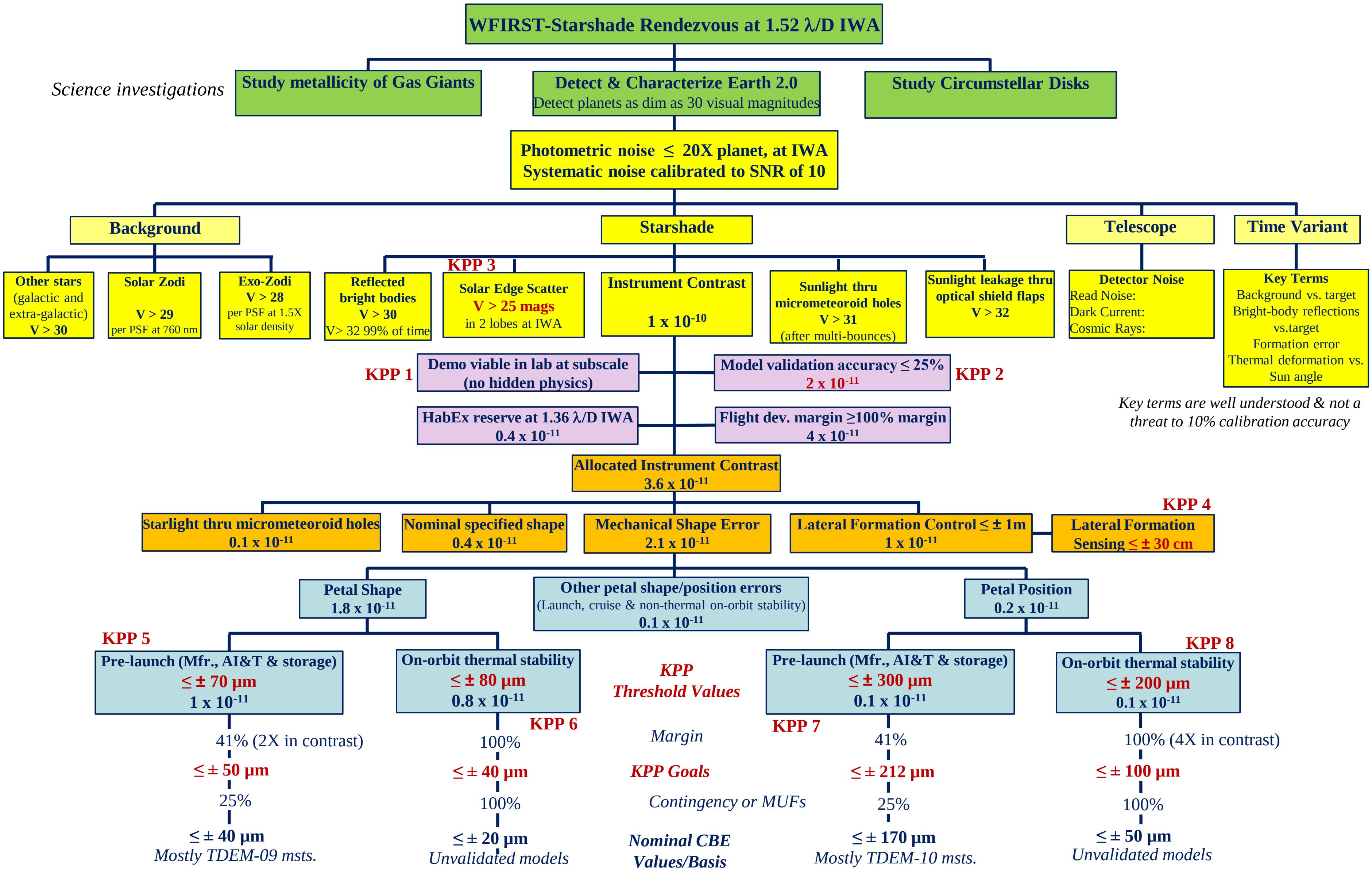


Regarding the solar cell IMM5J TRL:
- TRL7/8 in early 2019, and TRL9 expected by 2020
- SolAero: "…in preparation for full scale flight program using this IMM cell … accompanied by a full S-111 qualification*….

*S-111 qualification is the gold standard which was established by the Air Force, SMC, and NASA, and qualifies a given cell technology to the full range of space applications… ."



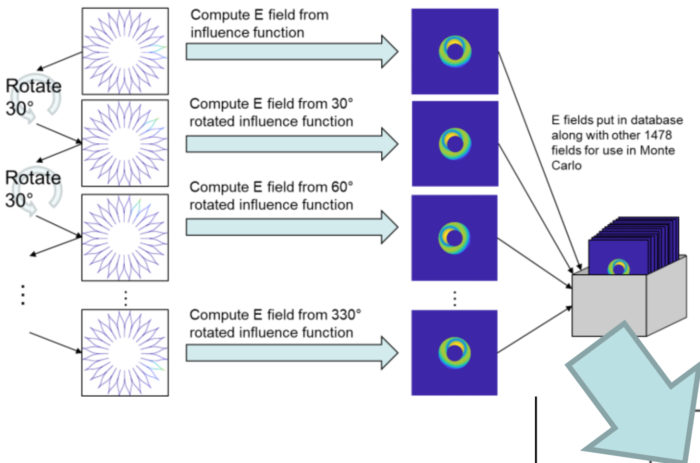
S5 Error Tree



S5 Key Performance Parameters

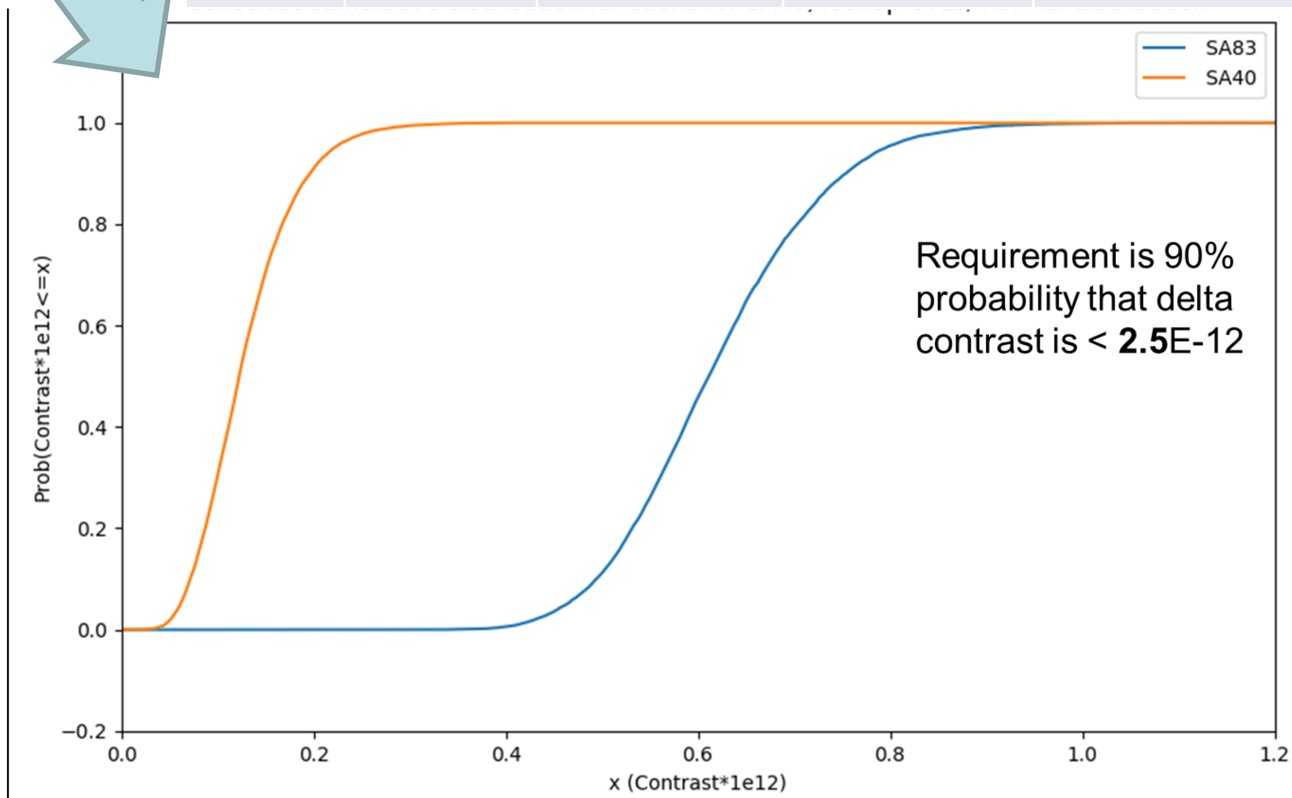
Technology Gaps	KPP #	KPP Specifications	KPP Threshold Values	KPP Goals
Starlight Suppression	1	Demonstrate flight **instrument contrast** performance is viable via small-scale lab-tests	1×10^{-10}	5×10^{-11}
	2	Validate **contrast model accuracy** relative to flight-like shape errors	≤ 25%	≤ 10%
Solar Scatter	3	Verify **solar scatter** lobe brightness visual magnitude	V ≥ 25 mags	V ≥ 26 mags
Lateral Formation Sensing & Control	4	Verify **lateral position sensor accuracy** and that it supports ± 1 m control via simulation	≤ ± 30 cm	≤ ±10 cm
Petal Shape	5	Verify **pre-launch accuracy** (manufacture, AI&T, storage)	≤ ± 70 μm	≤ ± 50 μm
	6	Verify on-orbit **thermal stability**	≤ ± 80 μm	≤ ± 40 μm
Petal Position	7	Verify **pre-launch accuracy** (manufacture, AI&T, storage)	≤ ± 300 μm	≤ ± 212 μm
	8	Verify on-orbit **thermal stability**	≤ ± 200 μm	≤ ± 100 μm

Monte Carlo of Contrast Response to CTE Variation with Temperature Mapping



Monte-Carlo Analysis Results:

Sun Angle	Samples	Prob contrast <=2.5e-12)	Mean contrast*1e12	90th percentile *1e12
83°	10000	100%	0.619	0.754
40°	10000	100%	0.130	0.196



STOP Analysis Results:

Sun Angle	Contrast*1e12
83°	0.588
40°	0.025

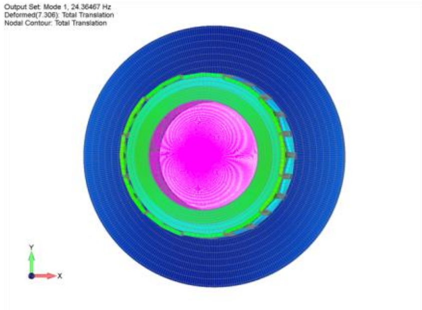
Stowed Configuration Modal Analysis

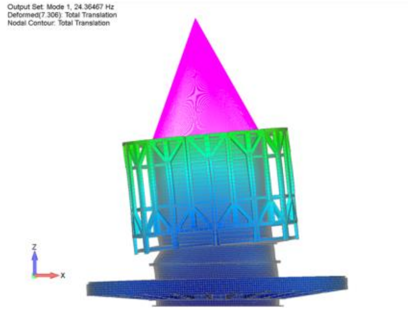
Dedicated Mission

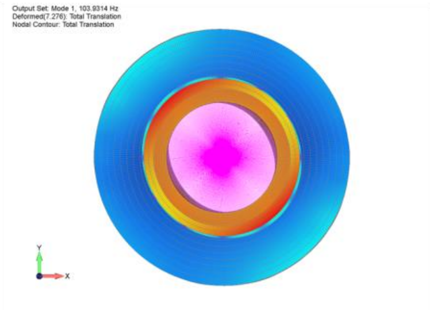
- The primary modes were also checked assuming the dedicated mission configuration
  - Telescope mass was taken from *"Exo-S STDT Final Report," Table 7.2-1*
  - Mass = 1,644 kg, Axial CG = 1.7 meters
    - Per Table 7.2-1, the propellant required for Starshade would decrease from 2000 kg to approximately 49 kg
    - Propellant mass in the FEM was conservatively left at 2000 kg
  - Impacts to the Petal tip, structural edge, and roller arm modes due to the additional telescope mass were negligible
- Critical frequencies and mass participation fractions
  - First primary lateral mode = 24.50 Hz (Mass participation = 1,770 kg)
  - First primary axial mode = 104.24 Hz (Mass participation = 2,842 kg)

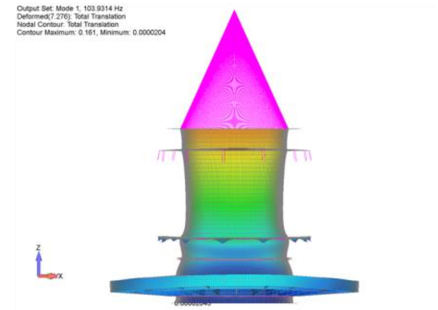
- Requirement: First primary lateral mode greater than 10 Hz
- First primary lateral mode
  - Frequency = 24.36 Hz
    - Mass participation = 619 kg (1,366 lb)
      - Mass participation fraction = 0.11
    - Additional lateral modes occur in this frequency range
  - Petals and roller arms are hidden for clarity

- Requirement: First primary axial mode greater than 25 Hz
- First fundamental axial mode
  - Frequency = 103.93 Hz
    - Mass participation = 1,709 kg (3,767 lb)
      - Mass participation fraction = 0.30
  - Petals and roller arms are hidden for clarity









Stowed Analysis Summary

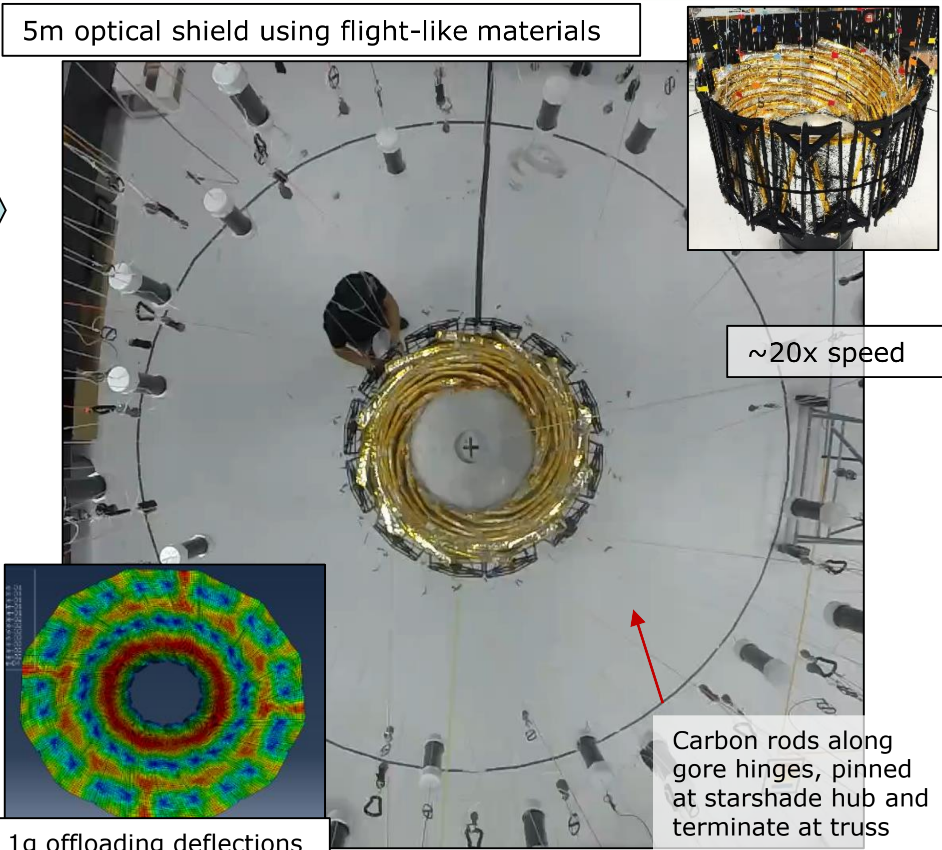
- Rendezvous Mission
  - 1st major mass lateral mode is at 51 Hz (Req’t 10 Hz)
  - 1st major mass axial mode is at 142 Hz (Req’t 25 Hz)
  - Strength margins of safety > 2.7 against falcon 9 user’s guide
  - Peak displacements within dynamic fairing envelope
  - Petal edge and tip relative displacements show large margin on petal to petal interaction
- Dedicated Mission (with telescope)
  - 1st major mass lateral mode is at 25 Hz (Req’t 10 Hz)
  - 1st major mass axial mode is at 104 Hz (Req’t 25 Hz)

Inner Disk Optical Shield Deployment & Simulations

5m prototype (1/2 flight scale):

- flight-like materials, learn about required features to enable flight design (e.g. gravity offloading & test)
- Understand shield, spacecraft, truss, & petal relative deployment and required features (e.g. carbon rods for hub/starshade structural connection, analysis pending)

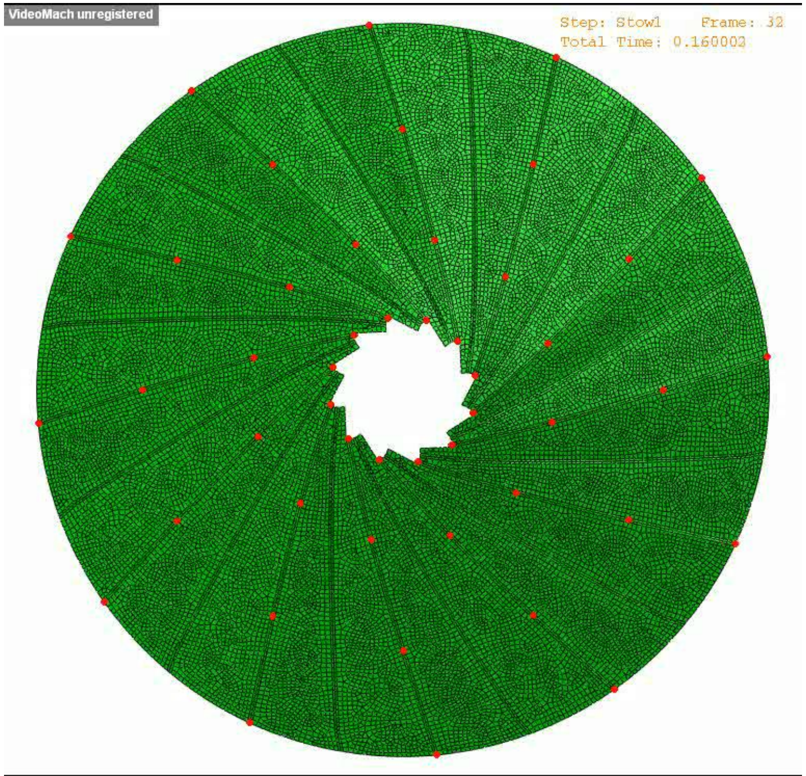
5m optical shield using flight-like materials



~20x speed

Carbon rods along gore hinges, pinned at starshade hub and terminate at truss

1g offloading deflections in Abaqus model



Deployment Simulation Model in Abaqus:

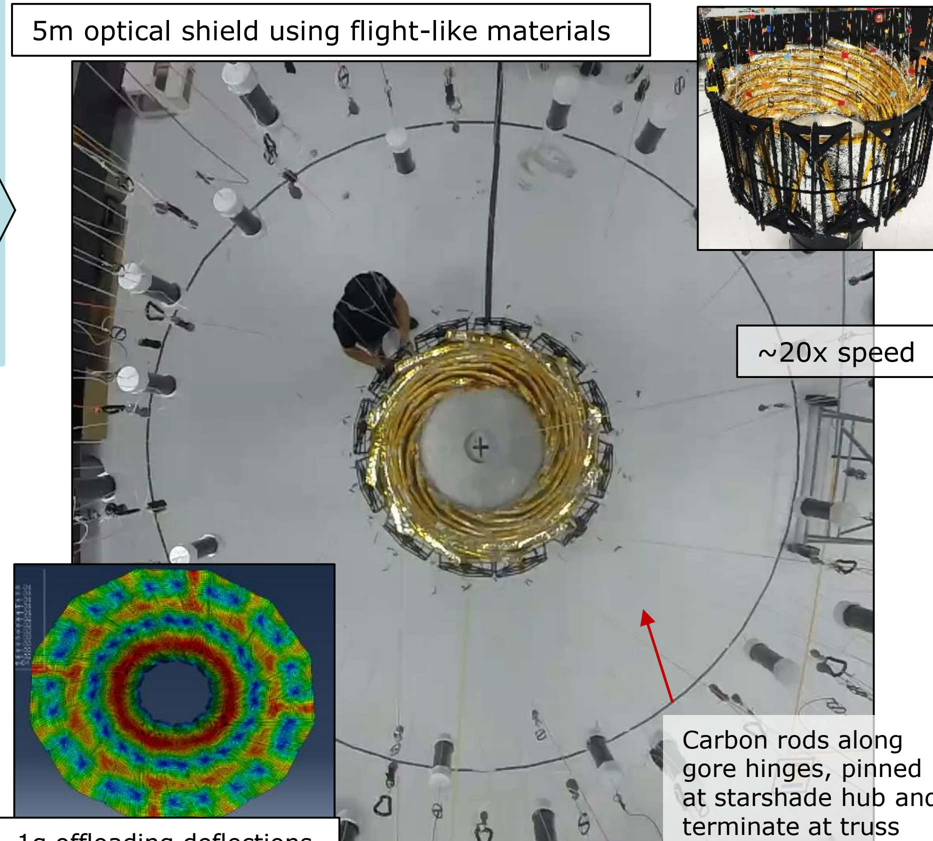
- Preliminary Abaqus deployment simulation model developed (T. Murphey) & utilized to understand 1g offloading
- Capability exists to combine a future, more developed model with the perimeter truss ADAMS model

Inner Disk Optical Shield Deployment & Simulations

5m prototype (1/2 flight scale):

- flight-like materials, learn about required features to enable flight design (e.g. gravity offloading & test)
- Understand shield, spacecraft, truss, & petal relative deployment and required features (e.g. carbon rods for hub/starshade structural connection, analysis pending)

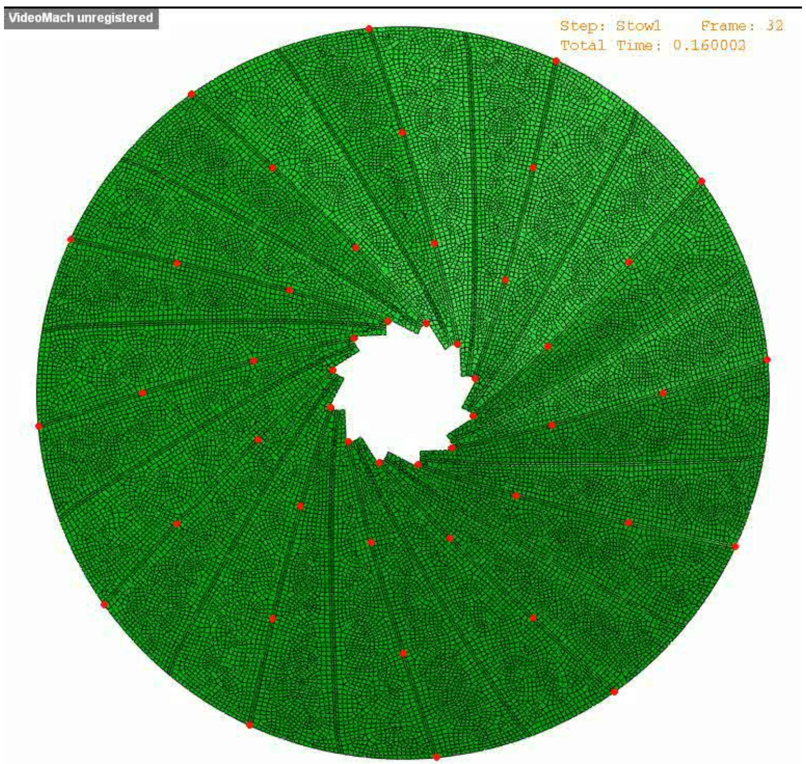
5m optical shield using flight-like materials



~20x speed

Carbon rods along gore hinges, pinned at starshade hub and terminate at truss

1g offloading deflections in Abaqus model



Deployment Simulation Model in Abaqus:

- Preliminary Abaqus deployment simulation model developed (T. Murphey) & utilized to understand 1g offloading
- Capability exists to combine a future, more developed model with the perimeter truss ADAMS model

Agenda

STOP analysis refresher of results for representative cases* :

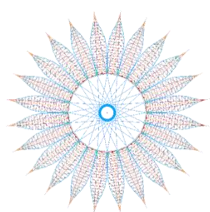
– Thermal analysis (temperature) results

– Thermal distortion results

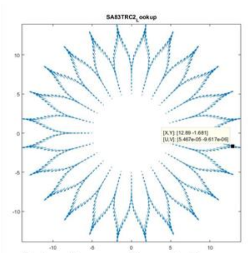
– Resulting contrast due to nominal thermal distortion & comparison to the error budget

- CTE variability monte-carlo study results

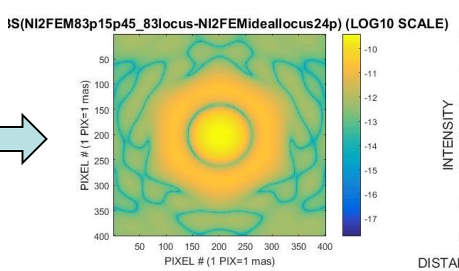
* Subset of sun angle cases showing representative temperatures & distortions/results, full set in backup

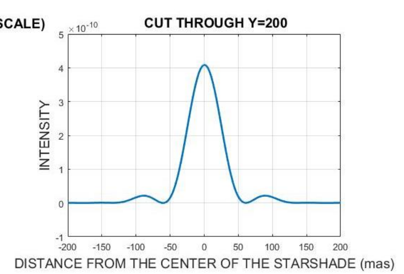


Thermal analysis temperature results mapped to structural FEM



Quiver plot of resultant thermally induced shape distortion

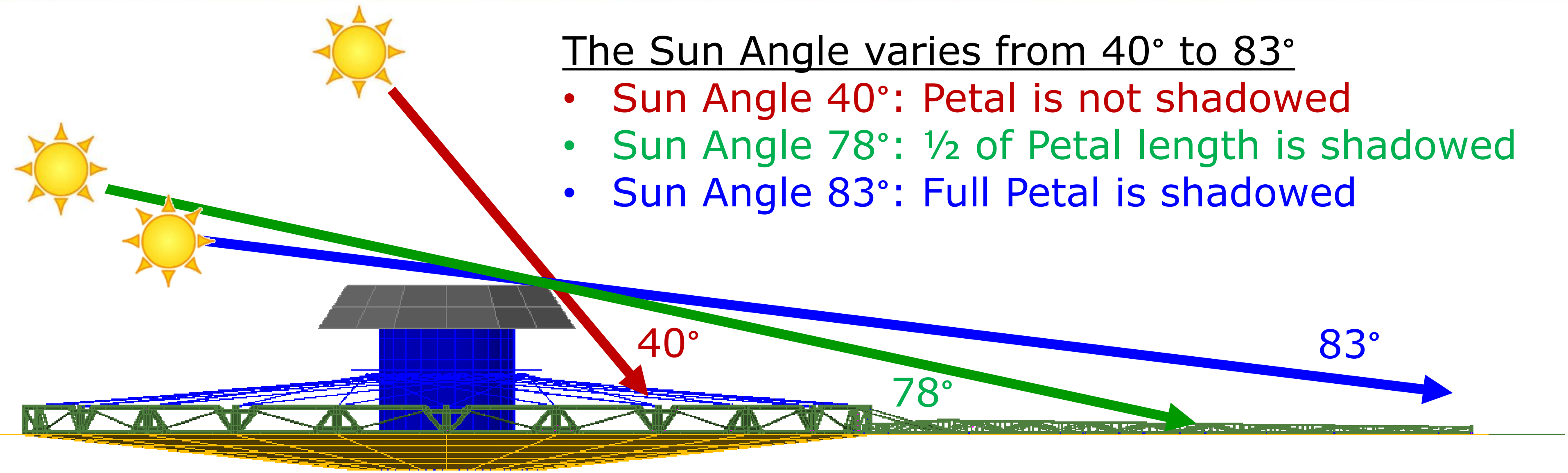




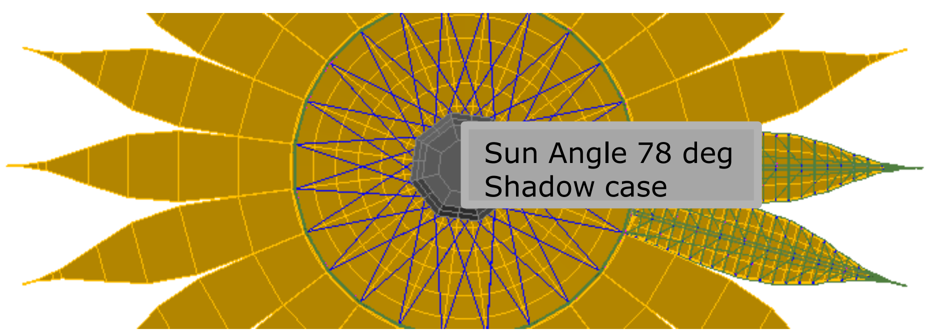
Sun Angles and Shadowing by Hub

<u>The Sun Angle varies from 40° to 83°</u>

- Sun Angle 40°: Petal is not shadowed
- Sun Angle 78°: ½ of Petal length is shadowed
- Sun Angle 83°: Full Petal is shadowed

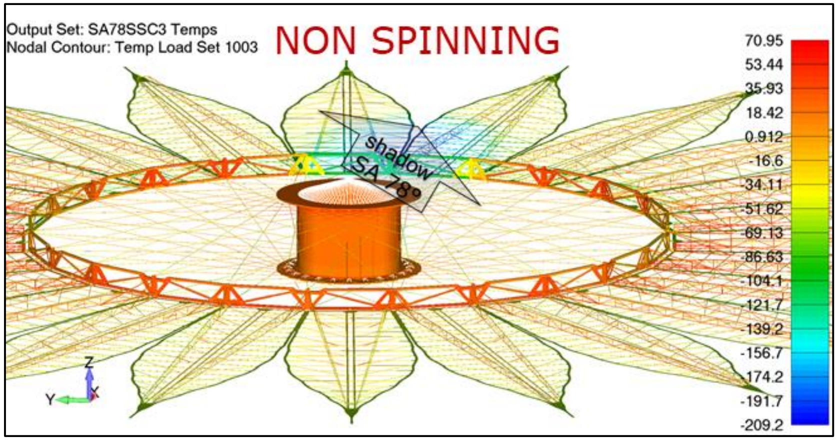


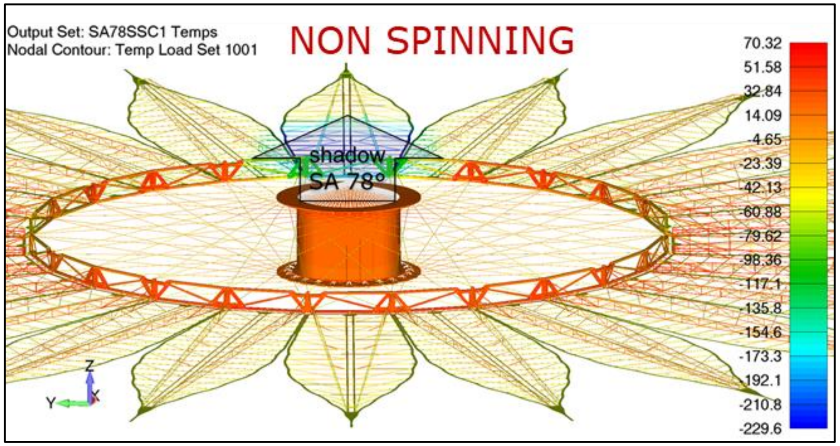
*** Slow rotation run every 3.75°. @1/3 RPM this is every 1.875 seconds, 96 positions. Temperatures available at each of the 96 locations.

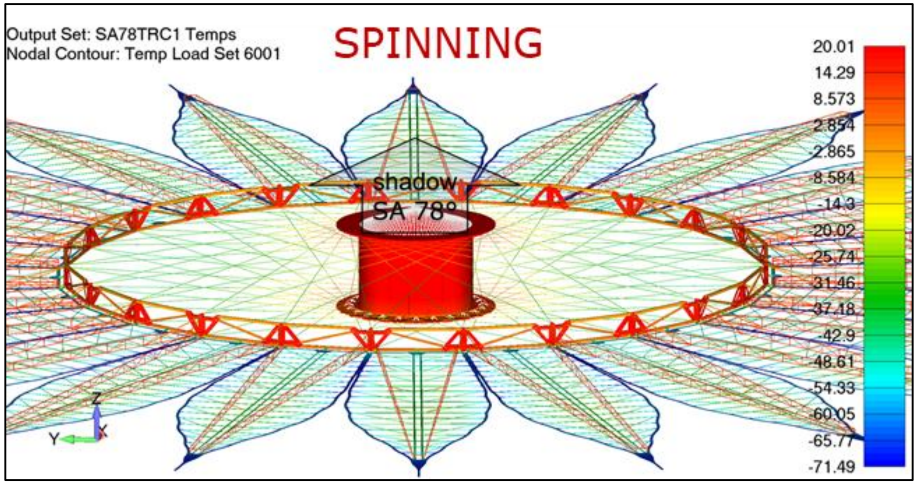


Non-spinning Shadow Orientation Conclusions

	Comment	Gradient	Max/Min Temp
NON-Spinning	Shadow clocking orientation has little effect on max/min temps, only moves cold portion of starshade	300 C	70 C / -230 C
Spinning	Averages temperatures symetrically aound spin axis Transient has negligible effect on contrast	90 C	65 C / -95 C







Sun Angle 78

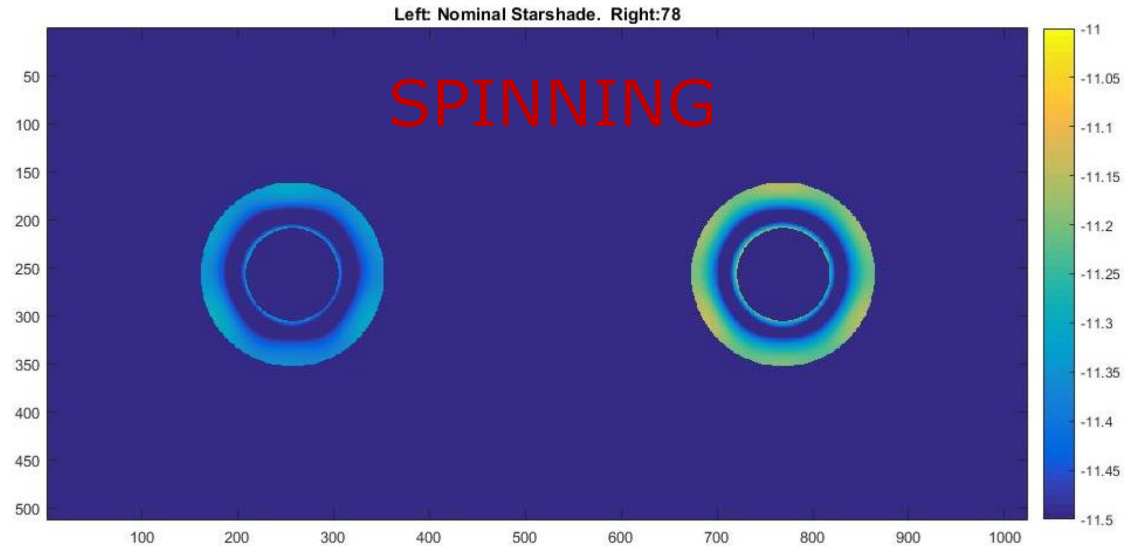
Comparison of Spinning to Non-Spinning

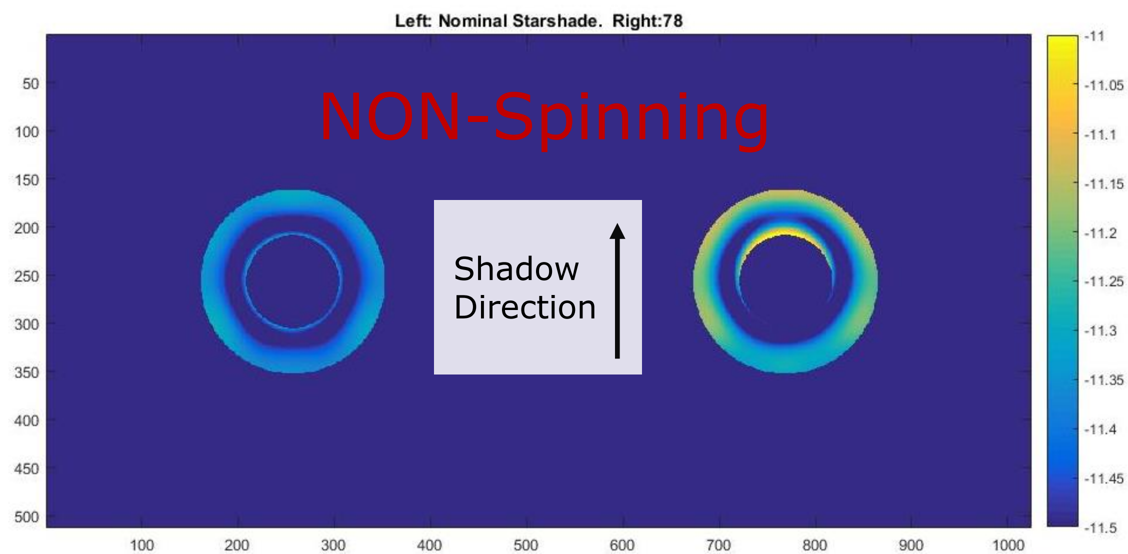
Spinning

- Spinning has a telescope axis-symmetric contrast
- Contrast varies radially

NON-Spinning

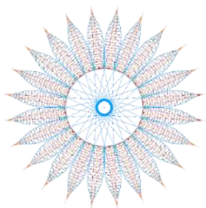
- Largely distorted shadowed petals :
  - Shift high contrast annulus toward shadow
  - Reduce contrast in petal distorted zone



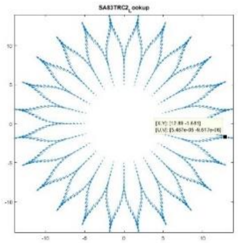


What did we do?

- Thermal elastic distortions are caused by the combination of temperature and CTE
- Thermal analysis results (temperatures) were mapped to the structural model
- CTE material cards were populated with CTE lookup tables, CTE vs temp
  - CFRP ply data test data characterization produces “nominal” CTE curves
  - Ply CTE data combines with layup to produce nominal layup CTE curve based CFRP layup design
  - Wrapped design utilizes 2 different layups
    - Structural Members (most) - Quasi-iso layup from NGAS
    - Optical Edge - Quasi-iso layup with the addition of the amorphous metal foil and 5 mil epoxy each side
    - Truss longerons - Quasi-iso layup with the addition three invar fittings that attach petal hinges
    - Uni-directional pultruded members utilized for JPL’s SWOT program
  - What about variation in CTE? Sensitivity to variation in mean CTE by layup type, and variation in CTE from component to component (for a given layup design) will be varied in a wide enough range to capture bounding variations and to check sensitivity to these bounds.



Thermal analysis temperature results mapped to structural FEM



Quiver plot of resultant thermally induced shape distortion

Thermal Distortion Contrast Results

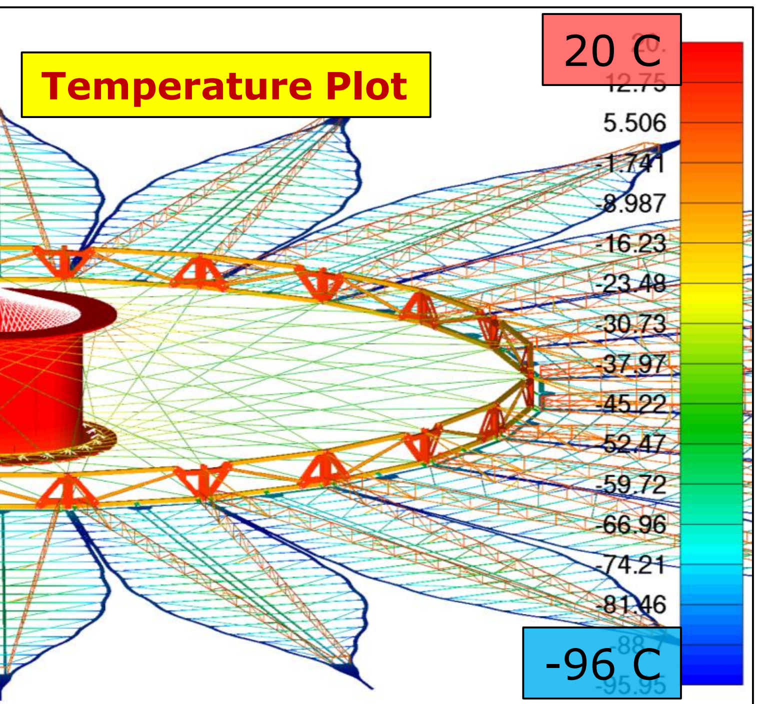
Case	***CBE*** *Delta Contrast x 1e-12*	***Max Expected*** *Delta Contrast w/ 100% contingency x 1e-12*	***Max Expected*** *% of Starshade Allocated Shape Error (3.4 e-11)***
Spinning			
40 deg*	*0.002*	*0.01*	*>1%*
78 deg	*0.398*	*1.592*	*4.6%*
83 deg*	*0.655*	*2.62*	*7.7%*
Non-Spinning			
40 deg	*0.06*	*0.24*	*>1%*
78 deg	*0.45*	*1.81*	*5.3%*
83 deg	*0.56*	*2.24*	*6.5%***

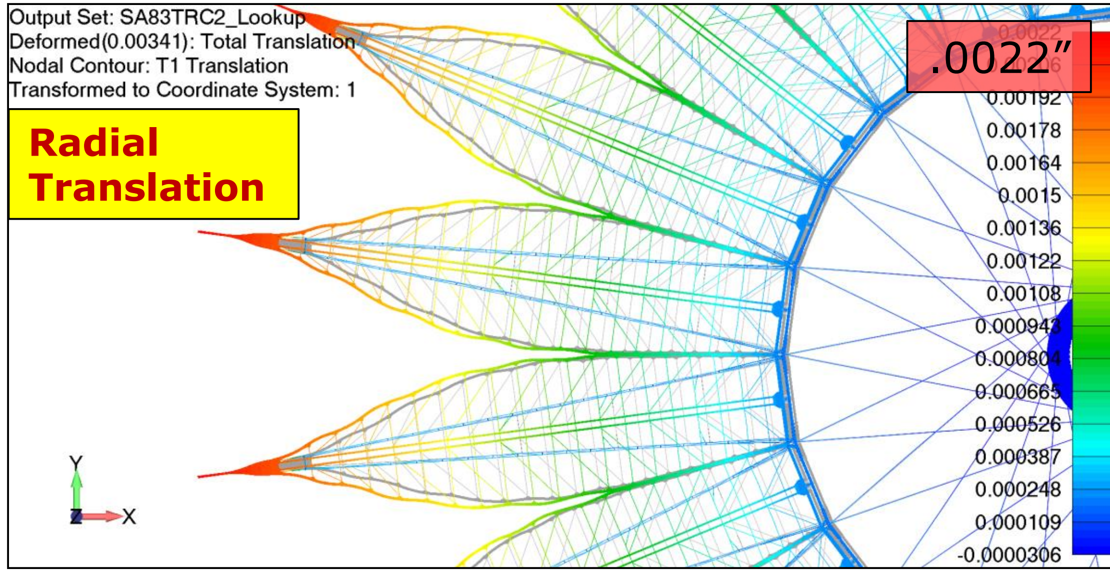
* Utilizes CTE for truss longeron w/ petal interface fittings affecting longeron CTE (w/no CTE design compensation)

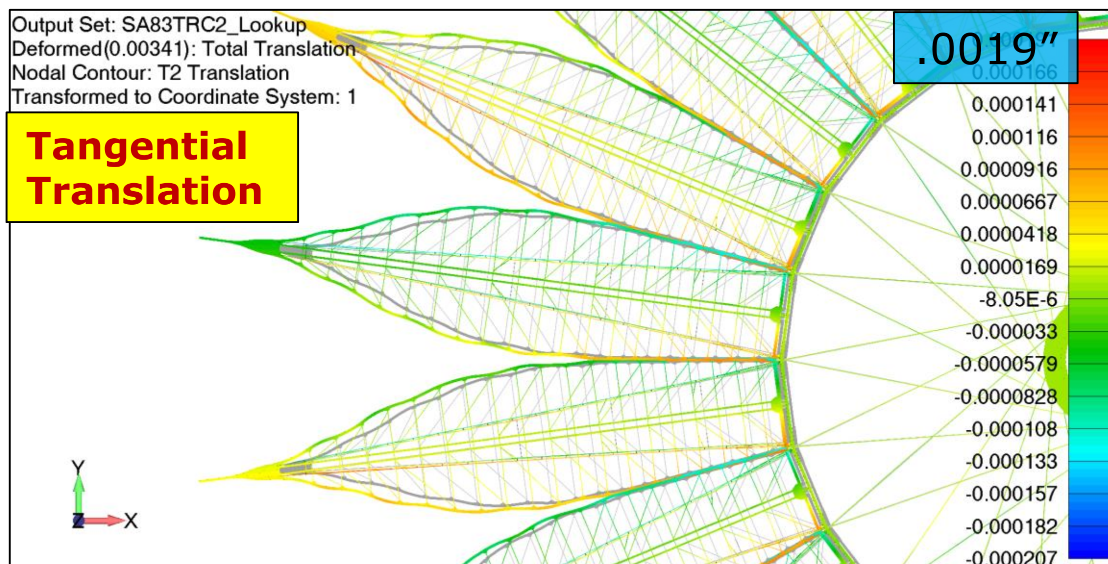
** Error budget carries CBE contrast from spinning results, non-spinning shown for reference only

SA83 SPINNING Distortions

- **Raw** distortions on order of 50 microns (0.002”)
- Distortions correspond to temperature results (thermal analysis), e.g.
  - Truss @ 20 C (room temp) = almost no shape change
  - Petal dT = -65 C, 50 microns (0.002”)

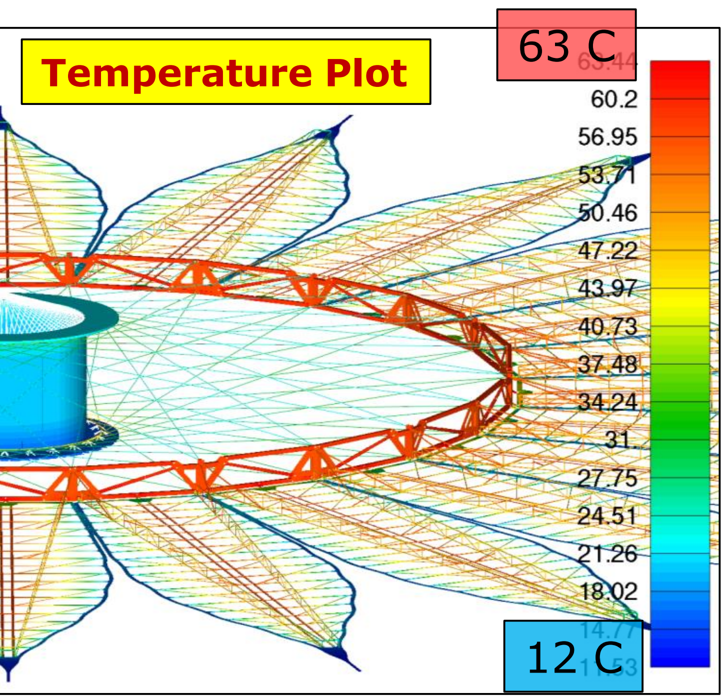


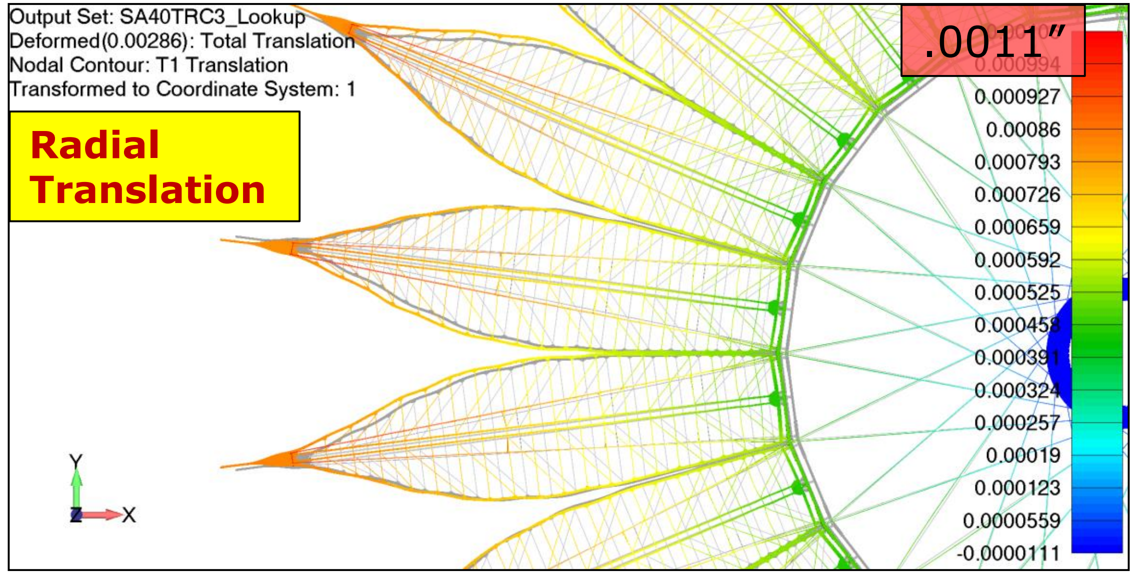


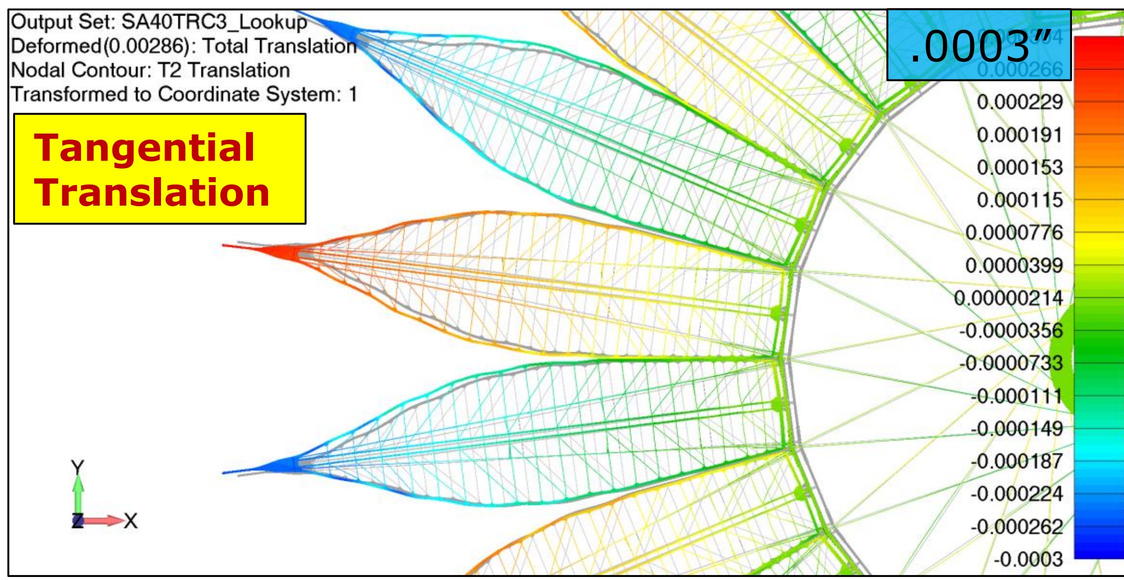


SA40 SPINNING Distortions

- **Raw** distortions on order of 50 microns (0.001”)
- Distortions correspond to temperature results (thermal analysis), e.g.
  - Truss @ 60 C (dT = 40C), ~25 micron radial expansion
  - Petal dT = ~+40 C, 30 microns (0.002”)

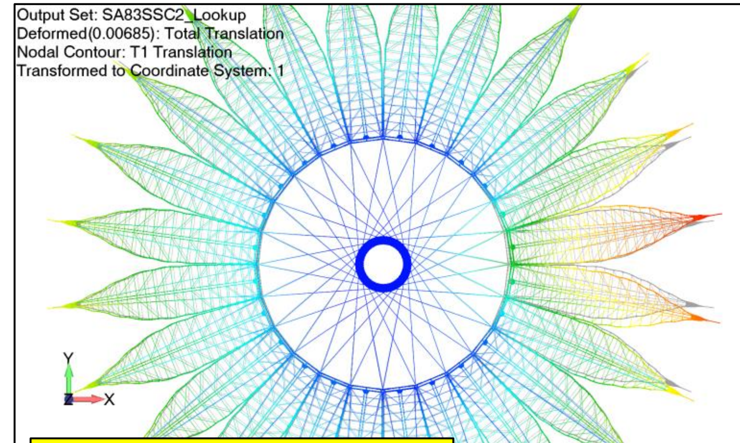


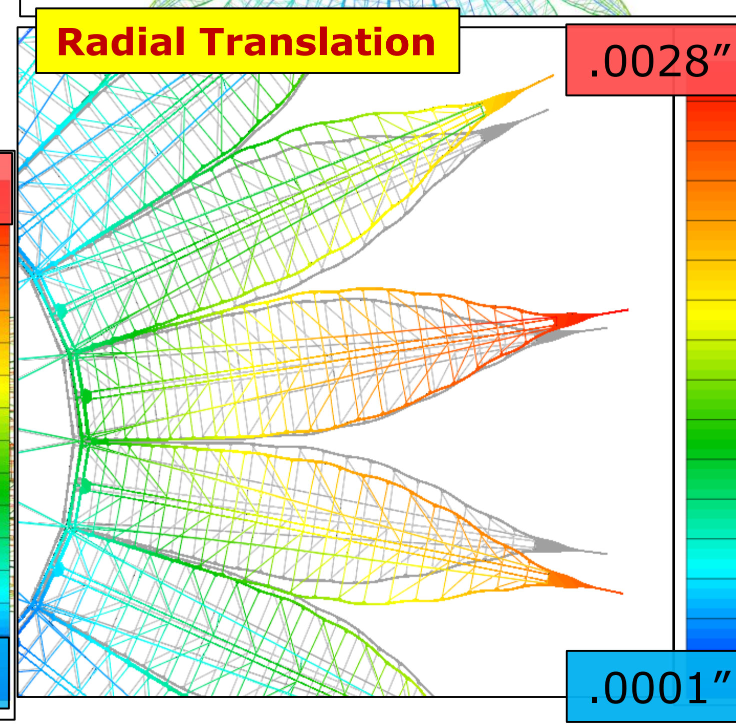


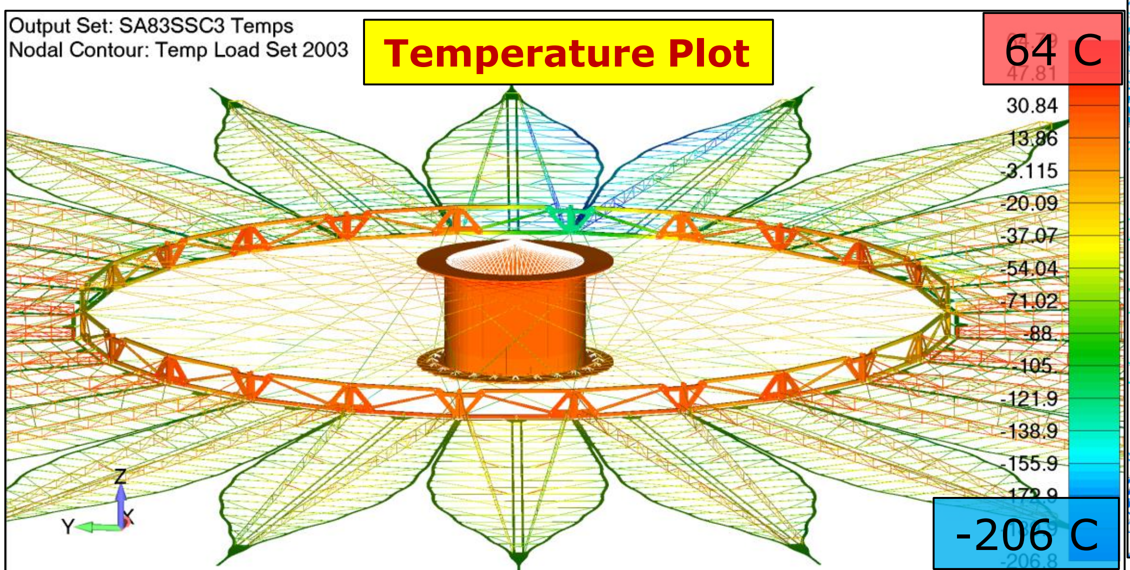


Sun Angle 83, NON-spinning, Distortions

- Sun Angle 83 degrees produces representative distortions and worst case contrast, shown as example of NON-spinning results
- **Raw** distortions on order of 75 microns (0.003”)
- Distortions correspond to temperature results (thermal analysis), e.g.
  - Truss HOT @ 70 C (dT = 50C), ~25 micron radial expansion
- Cold Petals are longer, disrupts apodization function

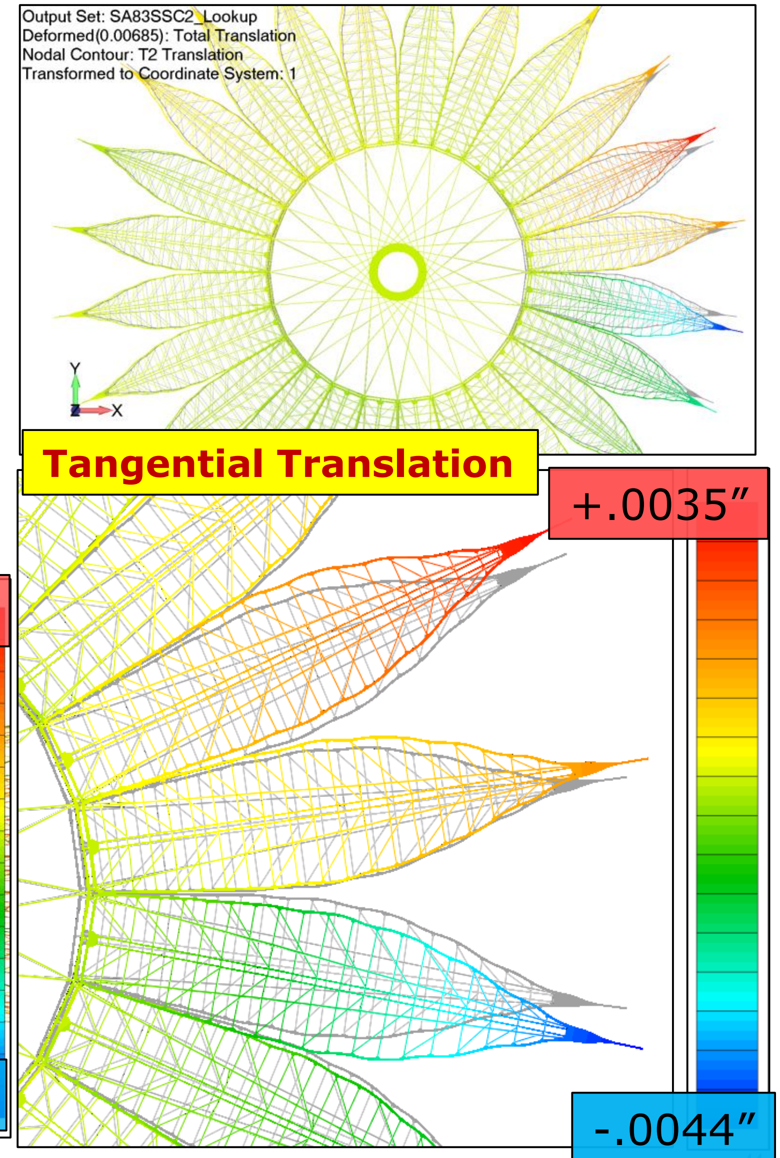


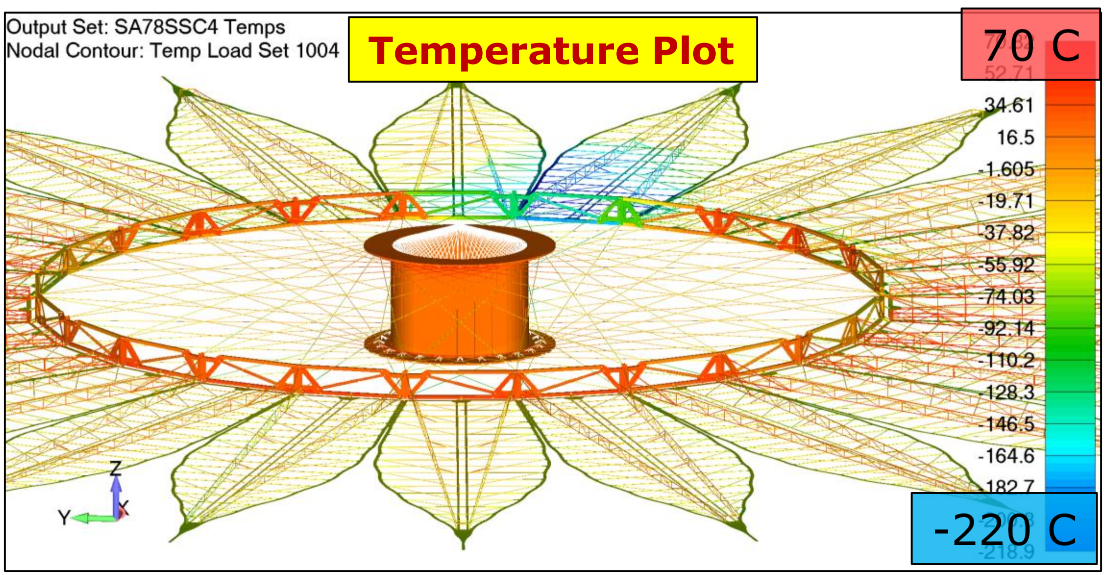




Sun Angle 83, NON-spinning, Distortions

- Sun Angle 83 degrees produces representative distortions for the steady state sun angle cases and is the worst case contrast for steady state, shown as example of NON-spinning results
- **Raw** distortions on order of 100 microns (0.004”)
  - Truss bays in shadow are cold, and grow (neg CTE), and splay petals apart from eachother





Summary

* Preliminary analysis shows max expected thermally deformed starshade meets requirements for both spinning and non-spinning configurations over working sun angles

Case	***CBE*** **Delta Contrast x 1e-12**	***Max Expected*** **Delta Contrast w/ 100% contingency x 1e-12**	***Max Expected*** **% of Starshade Allocated Shape Error (3.4 e-11)****
Spinning			
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* Utilizes CTE for truss longeron w/ petal interface fittings affecting longeron CTE (w/no CTE design compensation)

** Error budget carries CBE contrast from spinning results, non-spinning shown for reference only

Thermal Distortion Analysis

- Two analyses for the impact of thermal distortion on contrast:
  - STOP Analysis: uses thermal mapping and nominal CTE values (temperature dependent) to compute contrast for each sun angle
  - Monte-Carlo Analysis: uses random distributions on CTEs to determine statistical distribution on contrast for each sun angle